

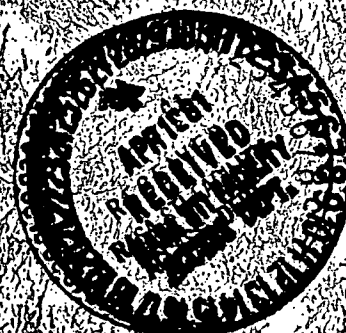
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ULTRASONIC RANGING
FOR THE
OCULOMETER

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ABSTRACT

Ultrasonic tracking techniques are investigated for the LaRC Honeywell Oculometer. Two methods are reported in detail. The first is based on measurements of time from the start of a transmit burst to a received echo. Knowing the sound velocity, distance can be calculated. In the second method, a continuous signal is transmitted. Target movement causes phase shifting of the echo. By accumulating these phase shifts, tracking from a set point can be achieved. Both systems have problems with contoured targets, but work well on flat plates and the back of a human head.

Also briefly reported is an evaluation of Polaroid's Ultrasonic Ranging system. Interface circuits suggested by Polaroid make this system compatible with the echo time design. While the system is consistently accurate, it has a beam too narrow for oculometer use. Finally, comments are provided on a tracking system using the doppler frequency shift to give range data.

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ABSTRACT

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ULTRASONIC RANGING FOR THE OCULOMETER

By

Warren J. Guy

I. INTRODUCTION

Studies currently in progress by the Flight Management Branch, FDC Division at Langley Research Center are successfully examining pilot "lookpoint" behavior. This work, initiated in the early 1970's, has provided information on pilot performance and instrumentation panel evaluations (1)-(4). The equipment selected initially in 1970 for these investigations was the Honeywell Oculometer, a large, complex system totally controlled by a NOVA 800 minicomputer (5).

The device, a non-intrusive eye tracking system, uses an infrared beam reflected from the retina. The pupil and corneal highlight image received by a TV camera is processed by the NOVA to calculate, via a long, complicated machine language program (6), lookpoint data and control signals.

In its current configuration, the Honeywell oculometer has two major shortcomings. First, the distance a subject is from a panel is unknown, causing errors in focus and lookpoint calculations. Second, when for some reason the oculometer loses the eye image, an elaborate searching scheme is initiated. This breaks the experiment and data is lost until the eye is recaptured. While these problems could be corrected by mounting some active device (an LED for example) on the subject's head, this would violate the non-intrusive philosophy of the studies. An additional complication in the system is its inability to process data and control the peripheral systems in the allotted time (1/60 sec).

Ultrasonic ranging and head tracking, the subject of this report, may offer a solution to the above problems by providing range information to the NOVA 800. The ultrasonic technique can also determine head position and thus directly control the TV focus and tracking mirror servo systems. By so doing, the computer may be freed of this burden, thereby providing more rapid eye recapture and reduction of computational time.

II. ECHO TIME SYSTEM

This system operates by measuring the time it takes a 40KHZ ultrasonic burst, approximately 1 msec long, to be echoed from a target. A simple transducer is first driven every 16.67 msec as a transmitter, see Figure 1. The transducer is next electronically switched to a receive mode; it then waits for an echo. Logic circuits determine the interval between transmit and receive signals and perform other gating and timing functions.

System operation will be discussed first, followed by a detailed description of the circuit.

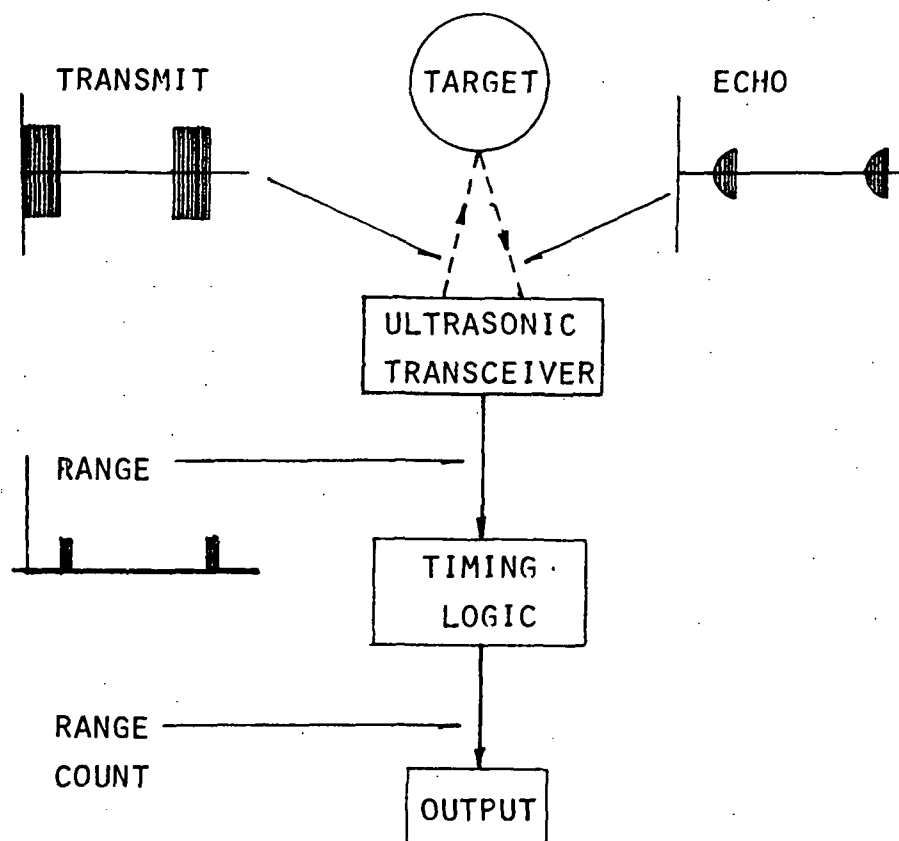


FIGURE 1 SIMPLIFIED ECHO-TIME SYSTEM

2.1 Echo-Time System Operation

System operation was evaluated under two testing conditions: static and dynamic target motion. Under each condition a variety of objects were tracked: flat metal plate, curved plate, styrafoam dummy head, and a human subject (both front and back of head). A flat plate, when oriented for maximum reflection, produced the best data. The back of a human head generated the best results for realistic applications. These latter two targets will therefore be used as bench marks with only occasional reference to other tests.

The static test uses "counts" for its final output data. Remembering that the actual distance to the target is twice that measured by the time interval between output and echo, counts can be converted to range using

$$R = \frac{C*v}{2*f}$$

where R = range

C = count

v = velocity of 40KHZ sound

f = clock frequency

A rule of thumb equation using 1000 ft/sec as the velocity of sound and a 20KHZ clock is:

$$R(\text{ft}) = C/40$$

Figures 2, 3 and 4 show contour plots of output count on a plane of range vs. angle. In these figures angular span was 15° left to 15° right with an actual range extending from 18" to 30" (corresponding to the 1 foot cube of the oculometer). The hyperbolic like curves define the 1 foot wide boarder in which the target is expected to remain. Data appearing in the field is the recorded count. The perfect system would produce straight, evenly spaced contours, parallel to the X (angle) axis.

Figure 2 shows the graph for a 6" x 12" flat metal plate target always oriented perpendicular to a radial line from the transducer. These results were the best obtained since no contour had a total variation of more than 1.0 inch. There is a slight nonlinearity in the spacing; at close range the countours are often separated by 5 counts/1.5 inches while farther out the separation

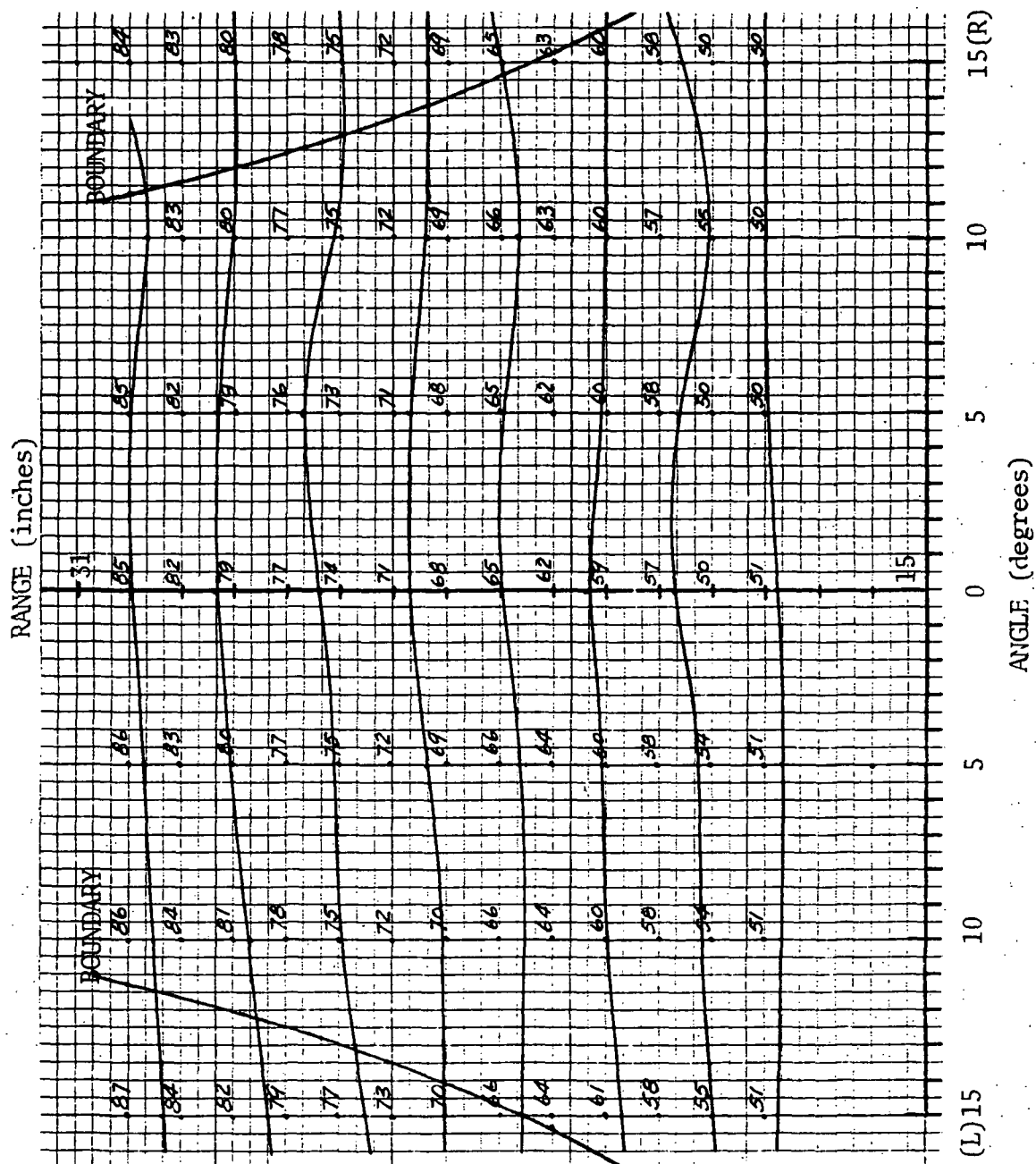
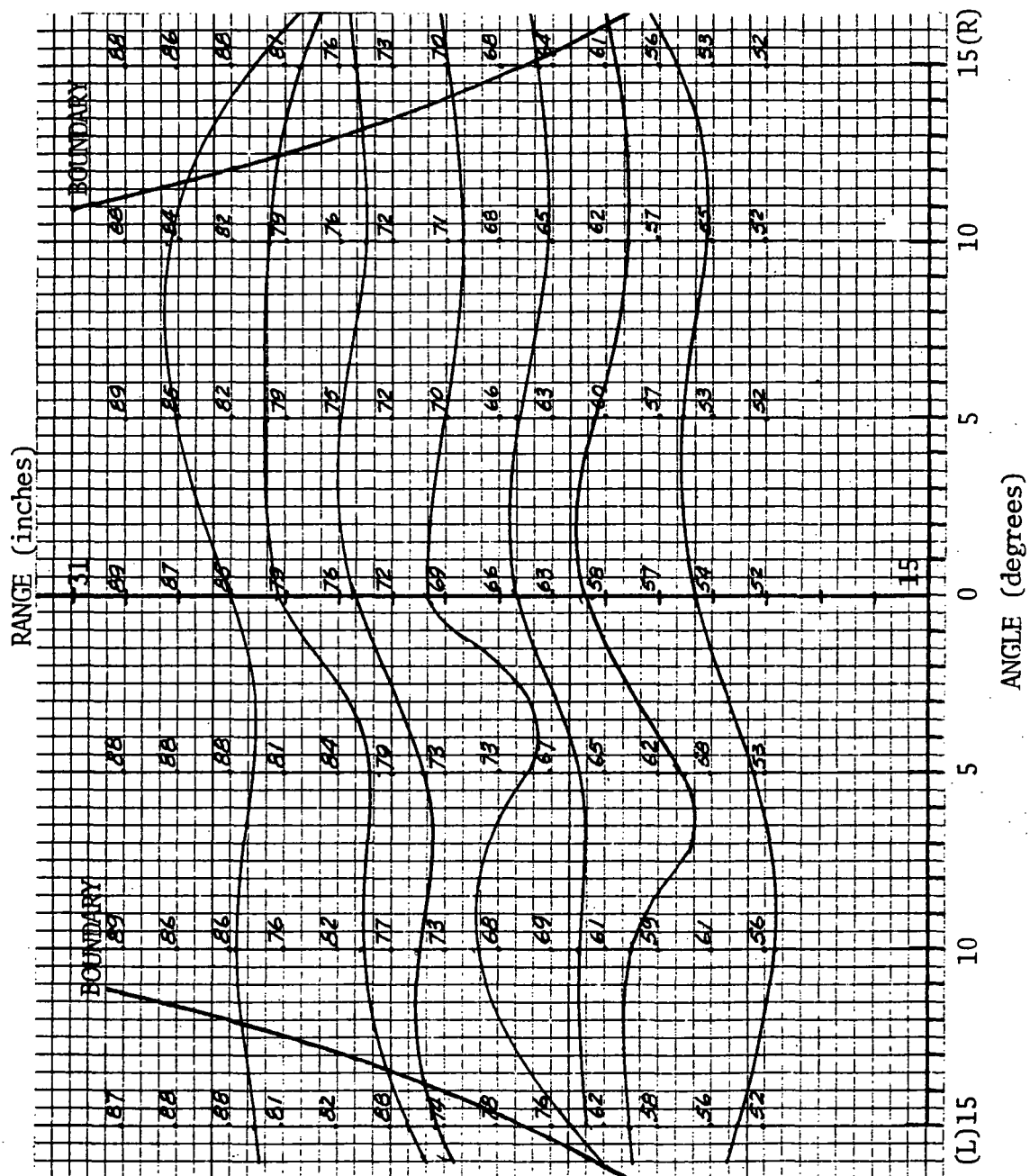


FIGURE 2. Echo-time system response

is 5 counts/2.0 inches. But even this does not violate the desired accuracy of ± 1.0 inch. The problem results because a strong close echo triggers the logic quickly, while the faint echo reaches threshold somewhat more slowly. (Polaroid solves this problem by using a time varying gain.)

In Figure 3 the data is for a styrafoam dummy head with nose and eye socket facial features. Angle/distance measurements were made to the left eye for the data shown; the head always faced directly at the transducer. Note that the right data field is fairly accurate, the largest errors being generated in the left data field. When the measurement is made to the right eye, this pattern reverses. These errors are produced by the complex echo signals from the human head. There seems to be no simple method around the problem, especially when head motion is added to complicate the signal. The difference between the actual range and that computed by the count equation can approach as much as 2". Some corrective algorithm may be possible if the angle to the

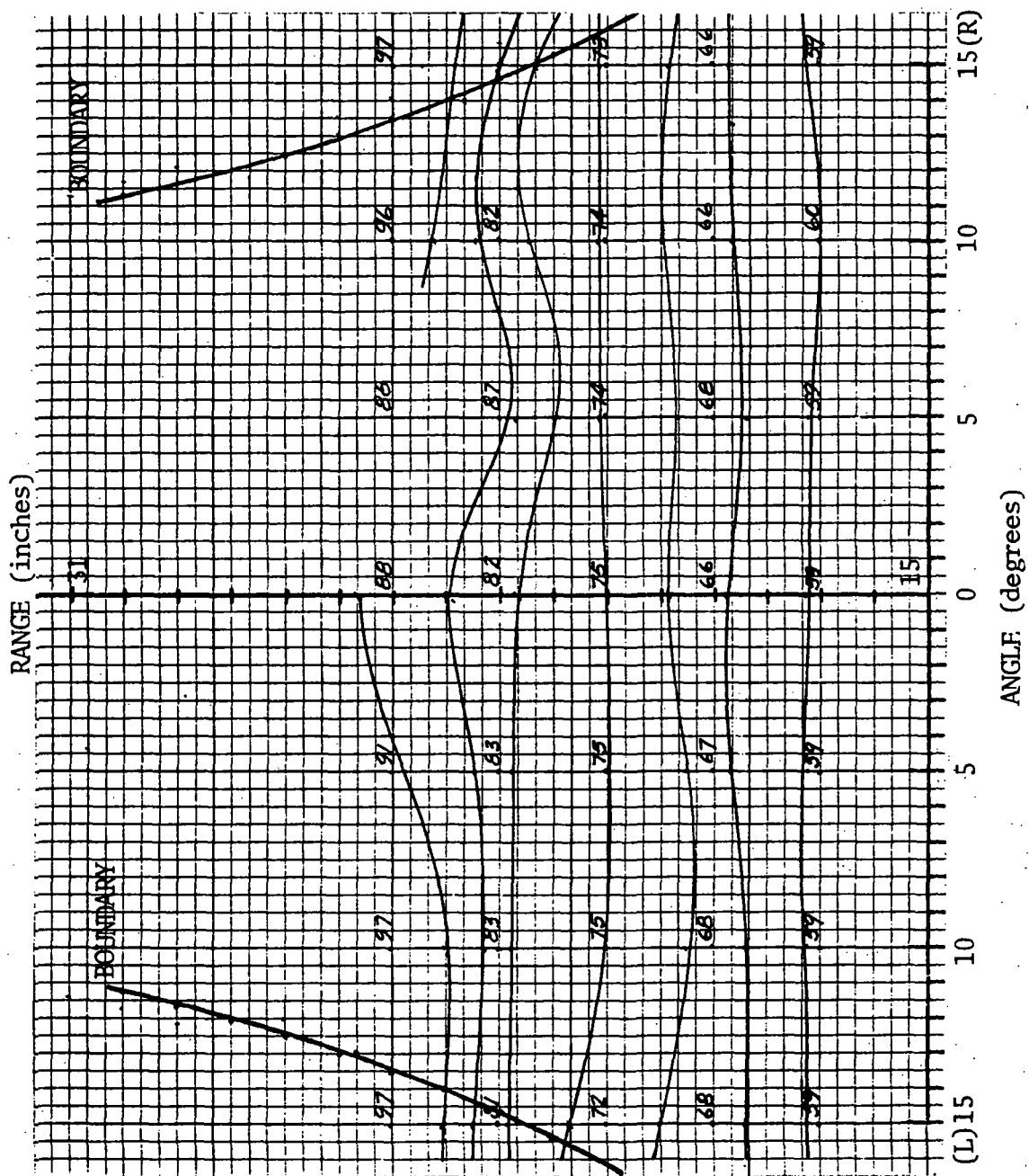


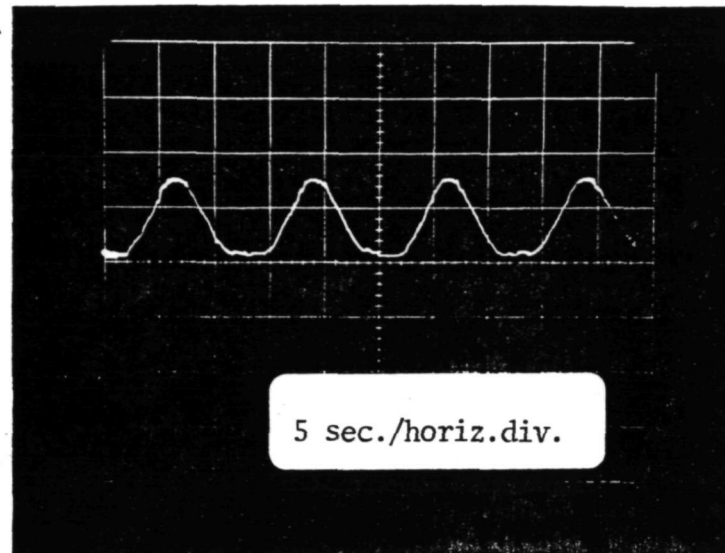
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target is known. This could be provided by the mirror drive circuit, but such an approach would lead to greater complexity. Since simplicity is the goal, other ranging methods should be considered first.

Figure 4 shows the results when the back of a human head is used as the static target. These results, while not as good as the flat metal plate, are far better than the frontal approach shown in Figure 3. Note that the most accurate contours are at close range which will probably be the situation for this method of tracking. As the range increases so does the count variation, reaching errors in the range of 1" near the outer boundaries of the tracking zone.

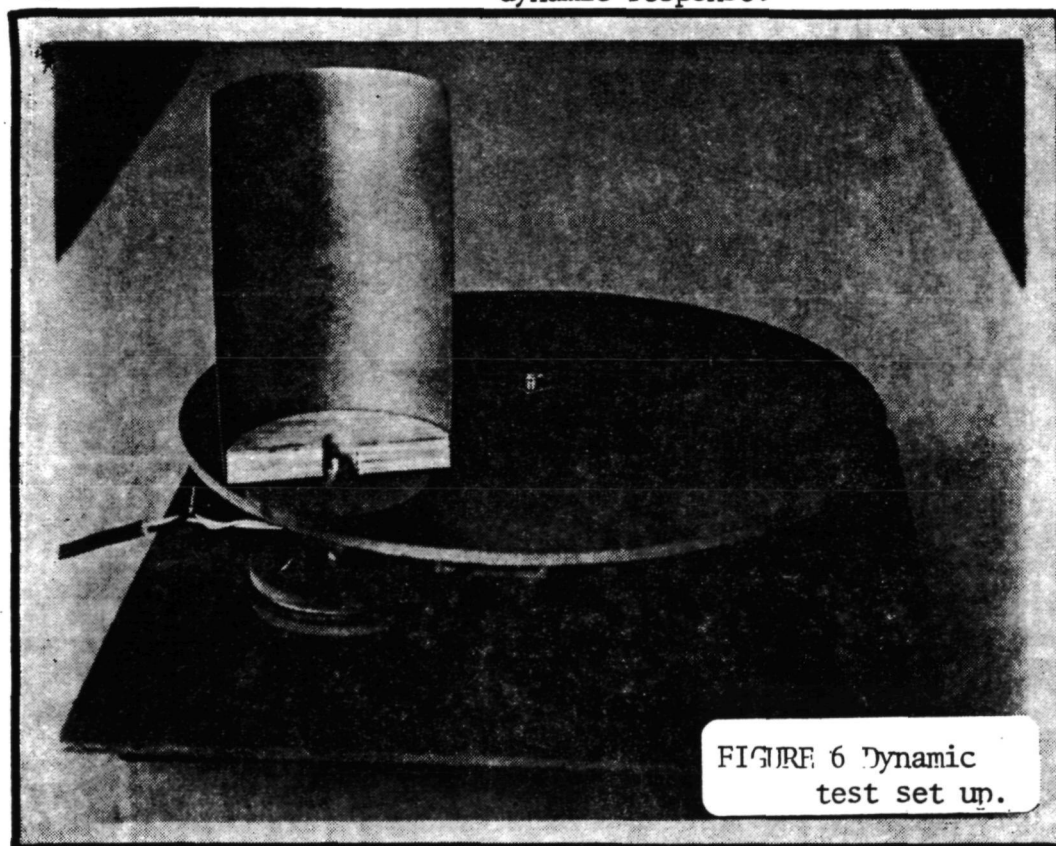
In the next two figures, the results of dynamic target testing are shown. Figure 5 is an oscilloscope trace of the filtered analog output of a DAC with the count as the input. The object tracked was a curved metal plate mounted on a 12" circular disc driven so as to keep the target oriented towards the transducer, Figure 6. The perfect signal would be a sinusoid. The results look good except for a nonlinear flattening at short range.





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FIGURE 5. Echo-time system
dynamic response.



In figure 7 is shown the results of an experiment which tracked a human head by a frontal approach. The top trace is the ultrasonic echo-time ranging system output. The bottom signal is from an electromechanical linkage to the target which gives "true" distance. As can be seen, the system performs satisfactorily. If the target strays outside the window, the ultrasonic system locks onto the last valid range data and produces a "flat" output.

A problem sometimes arose when the back of a head was dynamically tracked; i.e., a weak echo caused by different hair conditions and styles. In general, if a subject had a full head of hair, loosely styled, the echo was severely attenuated. Very often accurate, dynamic tracking became impossible.

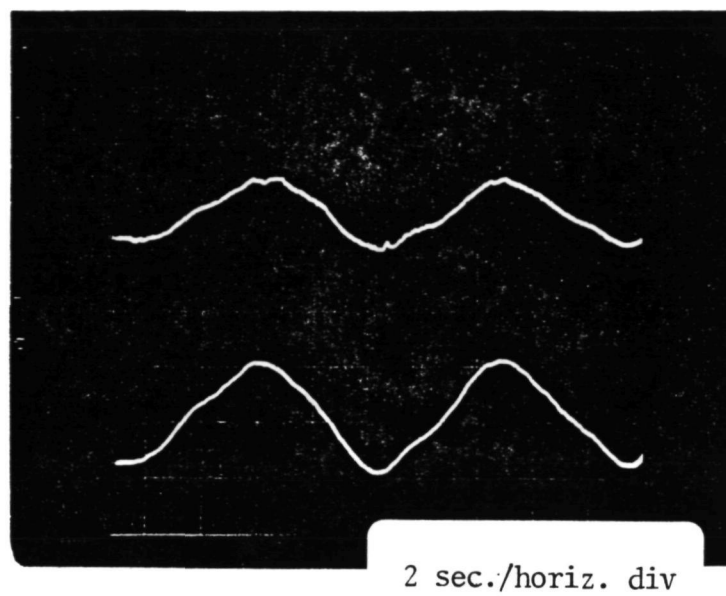


FIGURE 7. Echo-time system dynamic response.

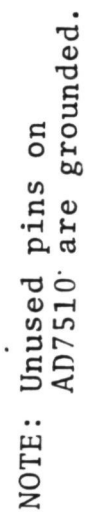
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2.2 Echo-Time Circuit Transceiver (TR), Figure 8

A single transmit/receive ultrasonic transducer is used in the system. The cycle is initiated by a start field (\overline{SF}) pulse synchronized with the oculometer video vertical sync ($f=60$ Hz). One half of a 556 (555 Timer) operates as a monostable, triggered by each \overline{SF} pulse. The output, a 1 msec pulse, drives the RESET of the second timer in the 556. It functions as an astable, tuned to the ultrasonic crystal (about 40 kHz); but only operates when the RESET is high during the 1 msec pulse from the first half of the 556.

To block the dc, the 40 kHz signal for 1 msec is capacitively coupled to an LM318 Op Amp. After amplification to approximately $\pm 15V$ peak-peak, the signal is switched to the transducer. The AD7510 analog switch is controlled by the 556 1 msec pulse, actively driving the output through a low impedance. When the switch is off, the transducer sees a high impedance looking back towards the LM318.

Both the transmit and echo signals drive the XR4558 Op Amp, but only the echo is eventually passed through a



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second switch in the AD7510. This switch is controlled by a window, W, signal generated on the timing logic board. Its time slice (which corresponds to a set distance) defines the valid echo range. Note that the XR4558 is driven into saturation during the transmit phase, but recovers in time to amplify the echo.

The echo, when returned during the window period, is compared in the LM311 Comparator to an adjustable threshold. The threshold should be set just above the noise level. Output of the LM311 is a sequence of 40 kHz pulses, E, and is used to drive the timing logic board.

Timing Logic Circuit (TLC), Figure 9

An SR flip flop is SET by each SF pulse and RESET only on a valid echo, E, occurring during the window. The SR output gates a clock (555 timer set to about 15 kHz) to the 74393 counter. The counter is RESET at the beginning of each cycle by the SF pulse. The count is latched into a 74100 by X, the SR RESET signal, only when a valid echo occurs. If no valid echo is received during the cycle, the last valid count is retained as the best current measurement. The 8 bit binary count is next displayed.



Binary-Decimal Display Circuit (BDD), Figure 10

An 8 bit binary input is converted to BCD (3 digits) by three 74185's. The 7447 then decodes the BCD digits to drive the three 7 segment LED displays through the 1 k ohm limiting resistors.

Also on this circuit board is a 555 timer (used as a 60 Hz pulse generator) to temporarily provide the \overline{SF} signal. A 7404 Hex Inverter then supplies the SF pulses.

Digital to Analog Conversion Circuit (DAC), Figure 11

To display the range data on the oscilloscope, the distance count from the digital board is input to a 1408 D/A converter. Its output drives a 741 current amplifier which in turn is connected to the scope. A simple RC filter has been added at the 741 output to smooth the signal.

Figure 12 is the edge connector and 16 dip cable connection configuration.

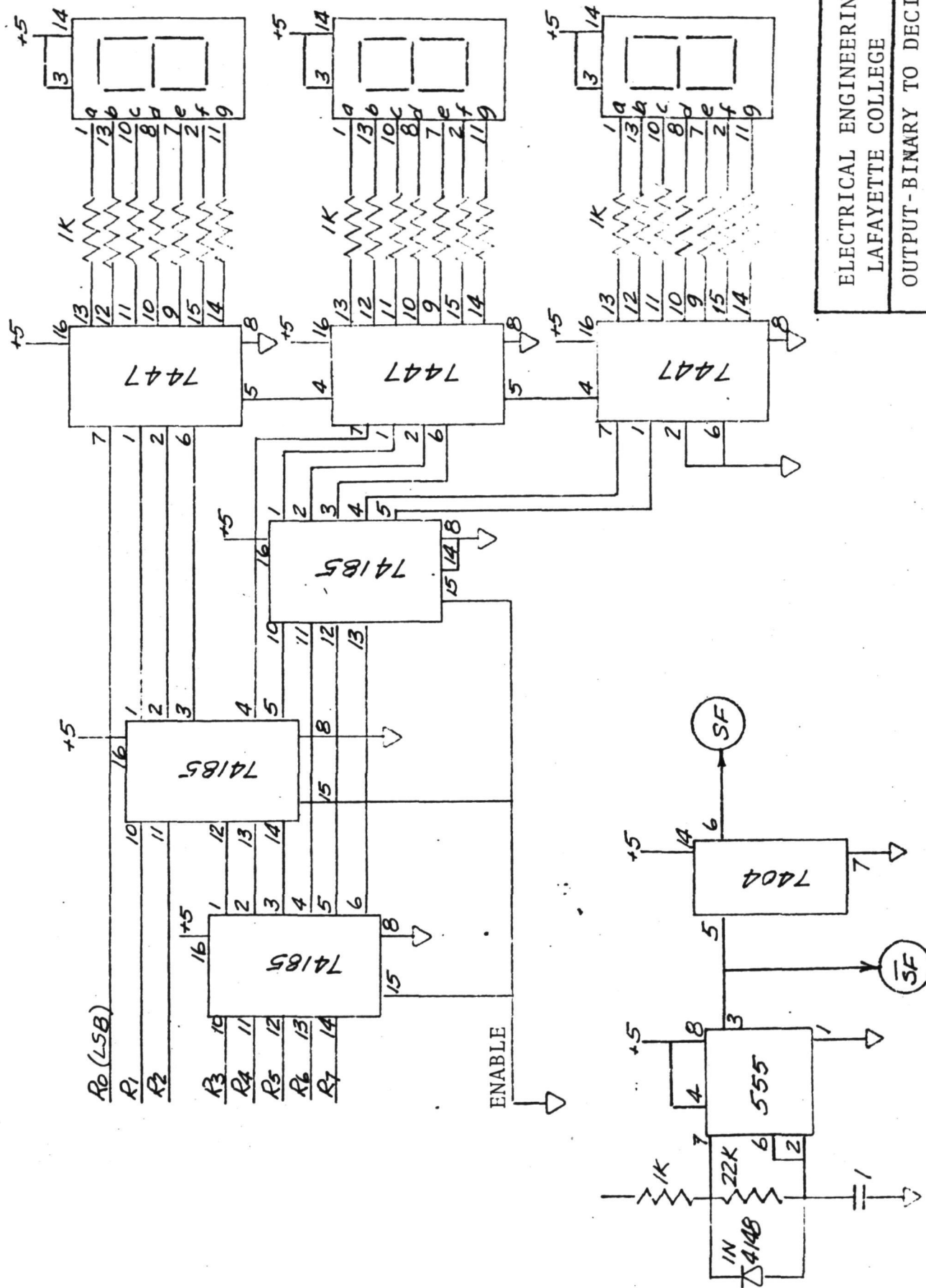


FIGURE 10

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OUTPUT-BINARY TO DECIMAL
DISPLAY CIRCUIT

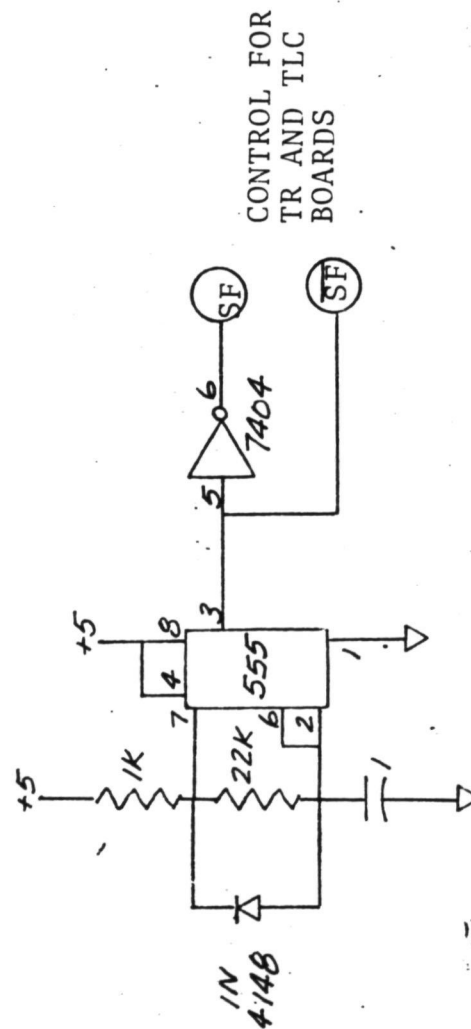
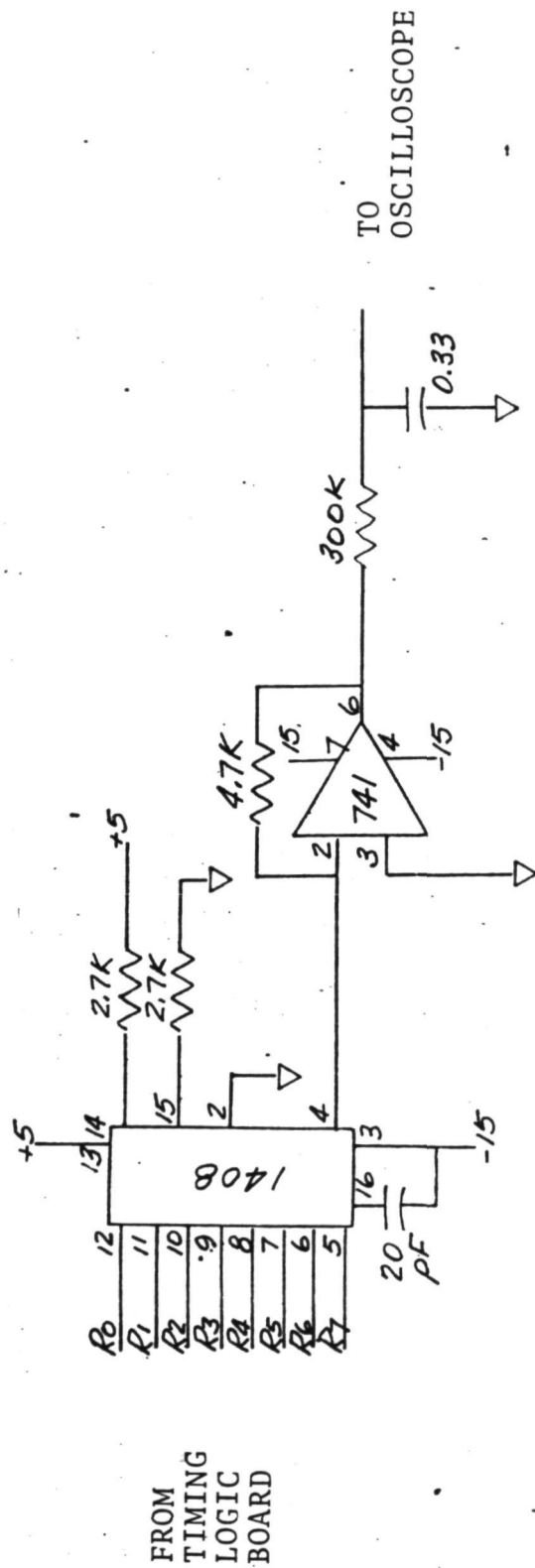


FIGURE 11

TR EDGE
CONNECTOR

1	+5	
2	GD	
3		
4		E
5		
6		
7		
8	+15	
9		
10		
11	GD	
12		
13		
14	-15	
15		
16		
17		
18	W	
19		
20		
21		SF
22		

POWER
STRIP

+5
GD.
+15
-15

TLC EDGE
CONNECTOR

1	+5	
2	GD	
3		R ₇
4	R ₂	R ₆
5	R ₄	R ₃
6	R ₅	R ₀
7		R ₁
8		
9		
10	SF	
11		
12		
13		
14		
15		E
16		
17		
18		W
19		
20		SF
21	GD	
22	+5	

DIP CABLE
CONNECTIONS

1	R ₁	R ₀	16
2	R ₃	R ₂	15
3	R ₅	R ₄	14
4	R ₇	R ₆	13
5	+5	SF	12
6	GD	+5	11
7	E	+5	10
8	SF	W	9

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BOARD CONNECTIONS

NAS1-45

12-24-80 wj.

FIGURE 12

2.3 Echo-Time System Signals

Figure 13 through 18 show selected signals in the each time system.

Figure 13 is the transmit signal at ultrasonic transducer. Time "zero" is at the left edge of the trace and defines the start of each cycle. The transducer is actively driven for approximately 1 msec and then shut off by the AD7510 analog switch. Note the exponential decay after shut off. System operation is very sensitive to the particular transducer (even within the same model line) especially during the receive cycle.

Figure 14 is the analog echo signal as seen on pin 7 of the XR4558 Op Amp. The target is a flat metal plate. Note the length of the residual echo. This causes false timing when the target is just in front of the window zone.

Figure 15 is the analog echo signal as seen on pin 7 of the XR4558 Op Amp. The target is a styrafoam dummy head. The shape of the echo is due to the contours of the dummy head. With a shallow depth of focus this will cause problems.

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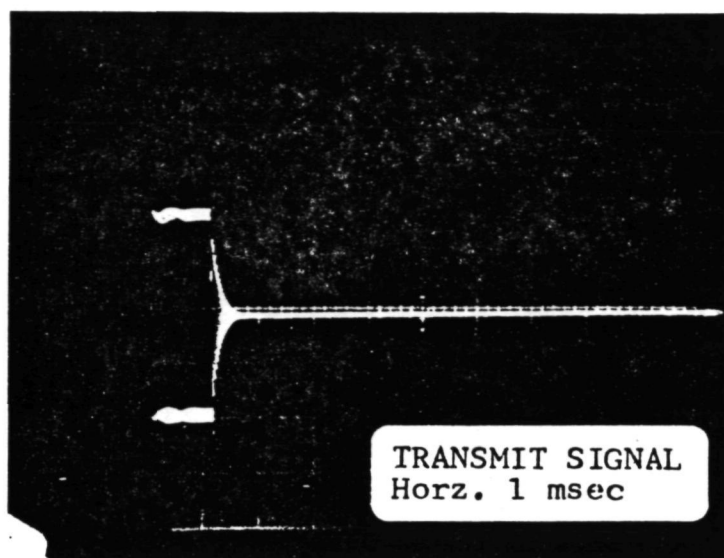


FIGURE 13

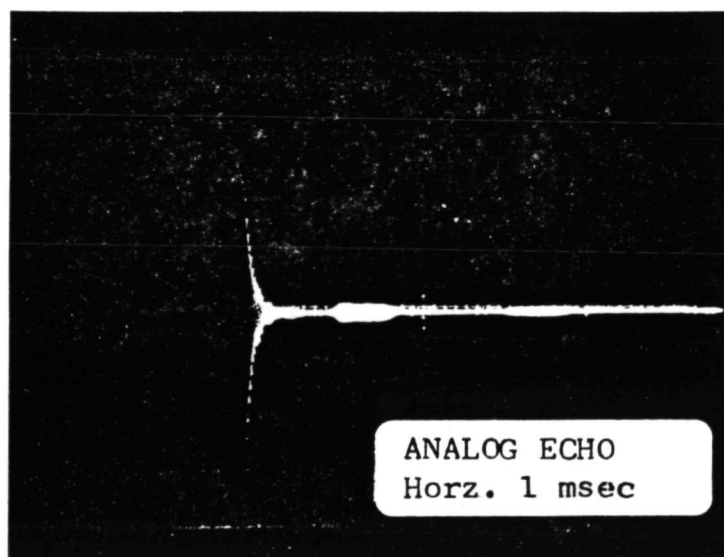


FIGURE 14



FIGURE 15

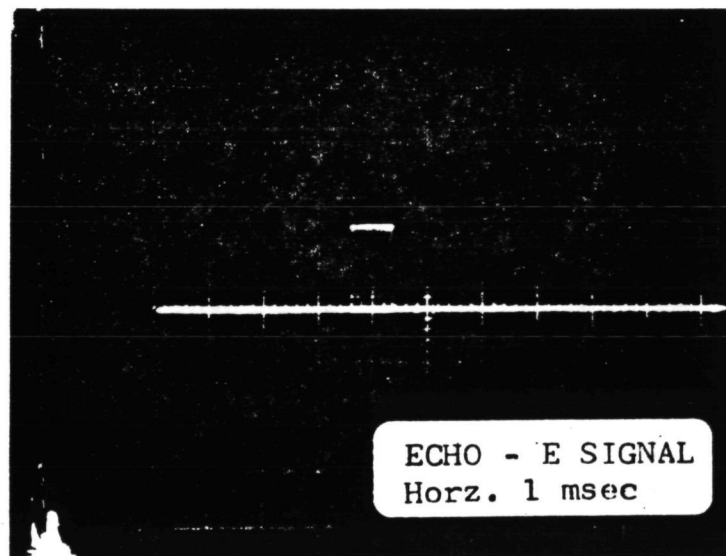


FIGURE 16

Figure 16 is the echo, E, signal generated by the LM311 comparator on the Transceiver circuit board, TR. The echo must be present during the window, W, in order to be valid. This sometimes leads to a response when the target is closer than that defined by the front edge of the window. It is caused by the long residual echo which occurs from all targets investigated and is in part due to the length of the transmit burst (1 msec).

Figure 17 is the window, W, signal generated by the 74123 on the Timing Logic circuit board, TLC. The window is adjustable between ranges set by a variable R and C. The width of the window is approximately 2 msec (about 2.2 foot round trip travel by the ultrasonic wave).

Figure 18 is the count, CNT, signal at pin 1 of the 74393 on the Timing Logic circuit board, TLC. The termination of the count is at the valid echo receive time. If the echo is not received within the window time, the counter is reset at the beginning of the next transmit cycle. Only valid echo times are latched into the 74100.

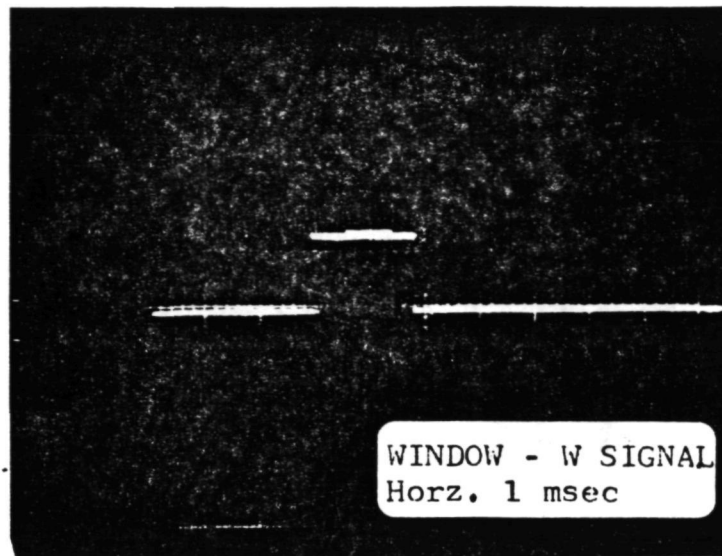


FIGURE 17

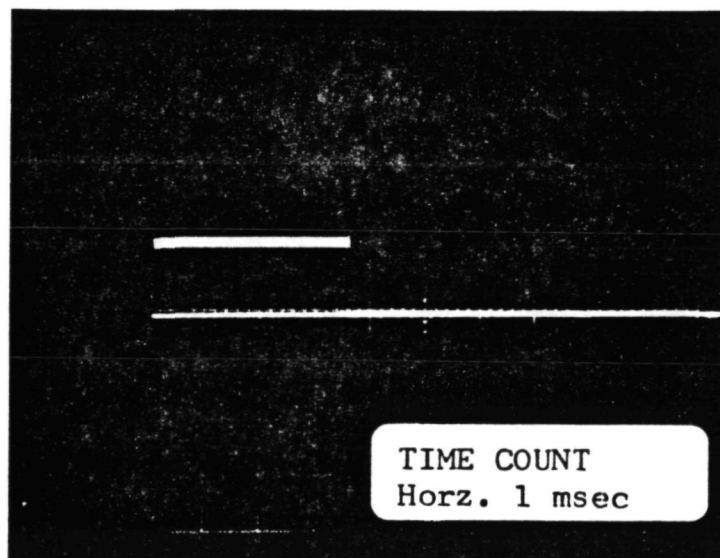


FIGURE 18

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2.4 Complete System

The completed system with a wire wrapped circuit on a plug board is shown in Figure 19.

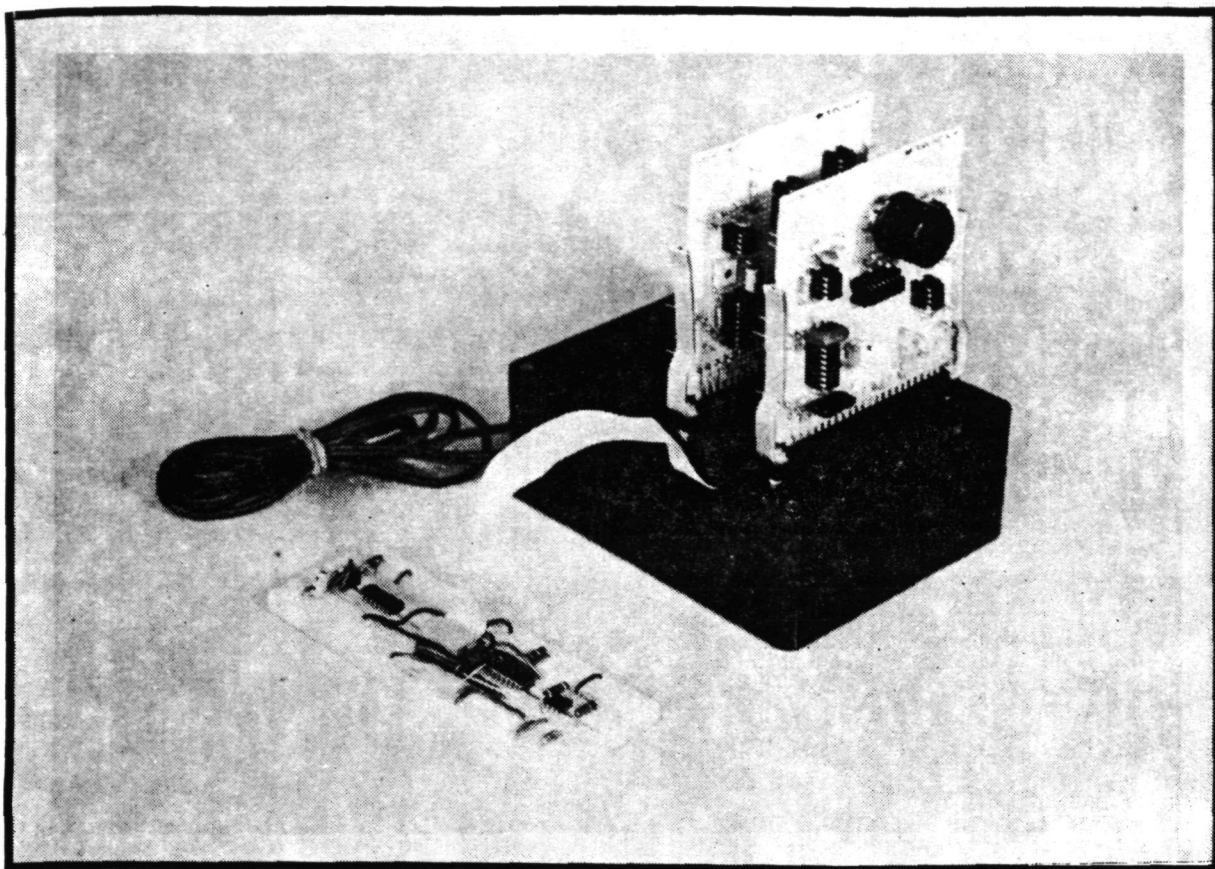


FIGURE 19 Echo-time system construction.
Bread board to the side is the
digital to analog converter.

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III. PHASE SHIFT SYSTEM

By employing separate, continuously transmitting and receiving circuits, a phase measurement can be made between two ultrasonic waves. Then, changes in the phase between the transmitted and echoed signals can be accumulated and the target tracked as it moves from some initially defined position, figure 20. Three methods to implement this idea have been investigated:

- (1) Wired logic
- (2) Direct phase measurement
- (3) Microprocessor based system

Results from a wired logic system are discussed, followed by a detailed description of the circuit. Finally, the direct phase measurement and microprocessor systems are briefly considered.

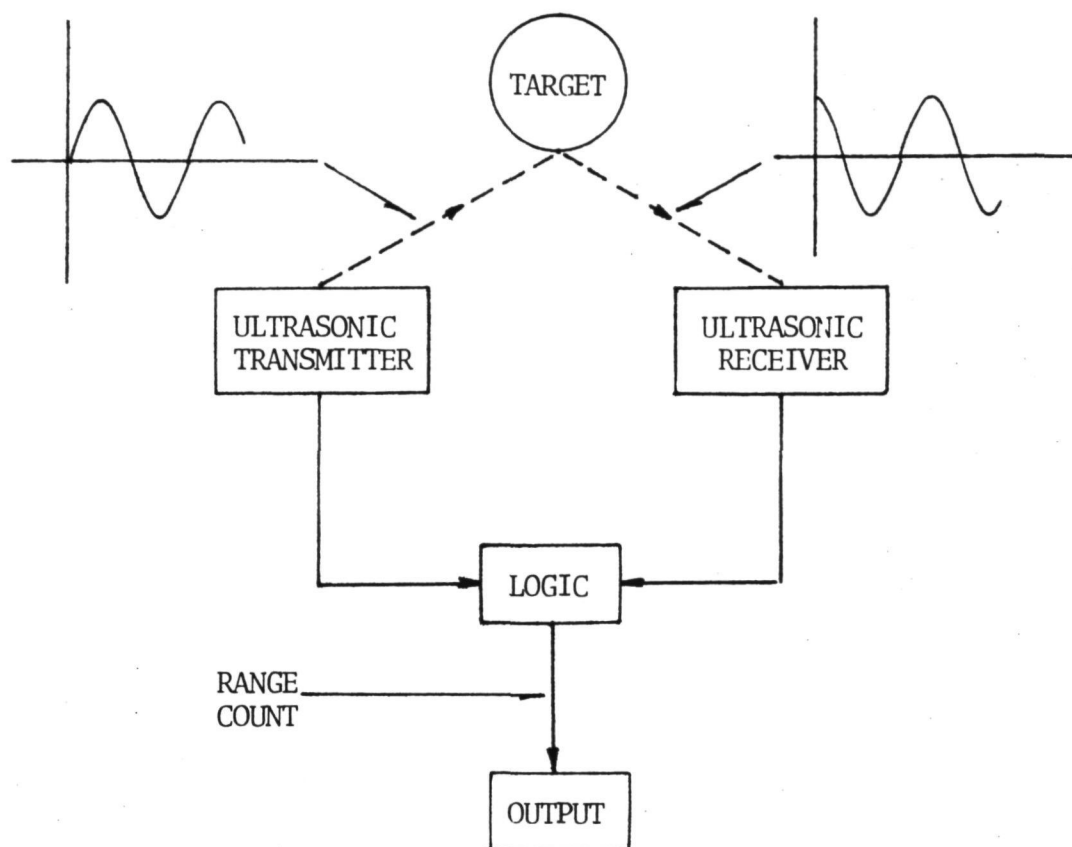


FIGURE 20 SIMPLIFIED PHASE-SHIFT SYSTEM

3.1 Phase Shift System Operation

This approach to ultrasonic tracking has the potential for greater precision than the echo time method. Basically the system counts the number of times the phase difference between a transmitted and echoed signal passes through the 0° point. If the phase increases from, say, 359° to 1° a counter is incremented by one. Conversely if the phase passes through 0° from 1° to 350° , the counter is decremented by one. Given that sound travels at 1130 feet per second, the 40KHz sound has a wavelength of 0.339 inches ($1130 \times 12 / 40,000$). Remembering that any movement of the target will actually produce twice the path for the sound wave, the system will theoretically keep track of incremental movement of about 0.17 inches.

To determine when the phase has crossed the 0° point, the phase difference is measured each cycle (every 25 μ sec) and converted to an arbitrary count. The count will range from 0 to 25 corresponding to 0° to 360° respectively. If during one cycle the phase count is less than 4 and then in the next cycle the count is greater than 20, it is assumed that a 0° crossing has occurred and the target is getting closer to the transducer. Conversely, going in the reverse direction produces opposite counts. These conditions then activate the UP/DOWN counter (see circuit description).

Using this phase shift system, a flat metal plate (6"x12") was tracked at 2 inches increments on radial lines spanning 30° . The experiment started by setting the counter to 128 when the plate was 18" from the transducer. The target was then incrementally moved to 30" and then incrementally returned to 18". The count should likewise return 128. Figure 21 shows the results of this experiment. The bottom number at each location is the recorded count as the target was moved from the transducer; that on the top is the count as the target was moved back towards the transducer. The count is very consistent and the results are as good as could possibly be hoped for. The contours are straight parallel lines equally spaced. The range spans 12" with a count of 60, or 0.2 inches per count. This is not far from the 0.17 inches theoretical value.

When a static test was tried with a Styrofoam head at distances greater than 18", many extraneous counts occurred as the target was moved in and out. These were apparently caused by the experimenter's hand and arm movements as the dummy head was moved about. Also, because the echo signals varied greatly as a function of face position, extraneous counting occurred in certain positions. Figure 22 shows the extremes of the echo signals. The top signal is clear, strong and well defined, while the

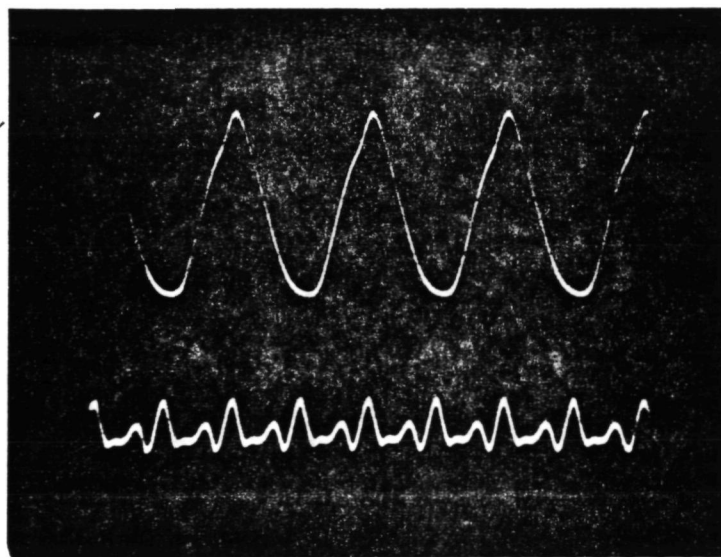


FIGURE 22. Echo patterns

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bottom signal, obtained from almost the same head position, is going to produce incorrect counts. Since such conditions would normally be expected when the system was in use, this ranging protocol was abandoned even for the static test.

As a substitute static test, a close range experiment was performed using the back of a Styrofoam head. This would simulate the conditions that would exist if ranging was performed by tracking the back of a human head. Figure 23 is a graph/table showing the results. As in the previous static test, the counter was set to 128 at the beginning of each run along a radial line. The starting point was 4 inches from the transducer with 1 inch incremental moves to 12 inches, then incrementally returning back to the start. The bottom numbers represent the count moving away from the microphone; the top numbers come from the return trip.

Note the sequence of numbers along each vertical (radial) line. They all start at 128 and decrease as the target is moved out. Due to some rewiring this is reversed from the previous static test, but the count direction is really inconsequential. The count varies from 5 to 6 per inch, again roughly a 0.2 inch increment. As this process

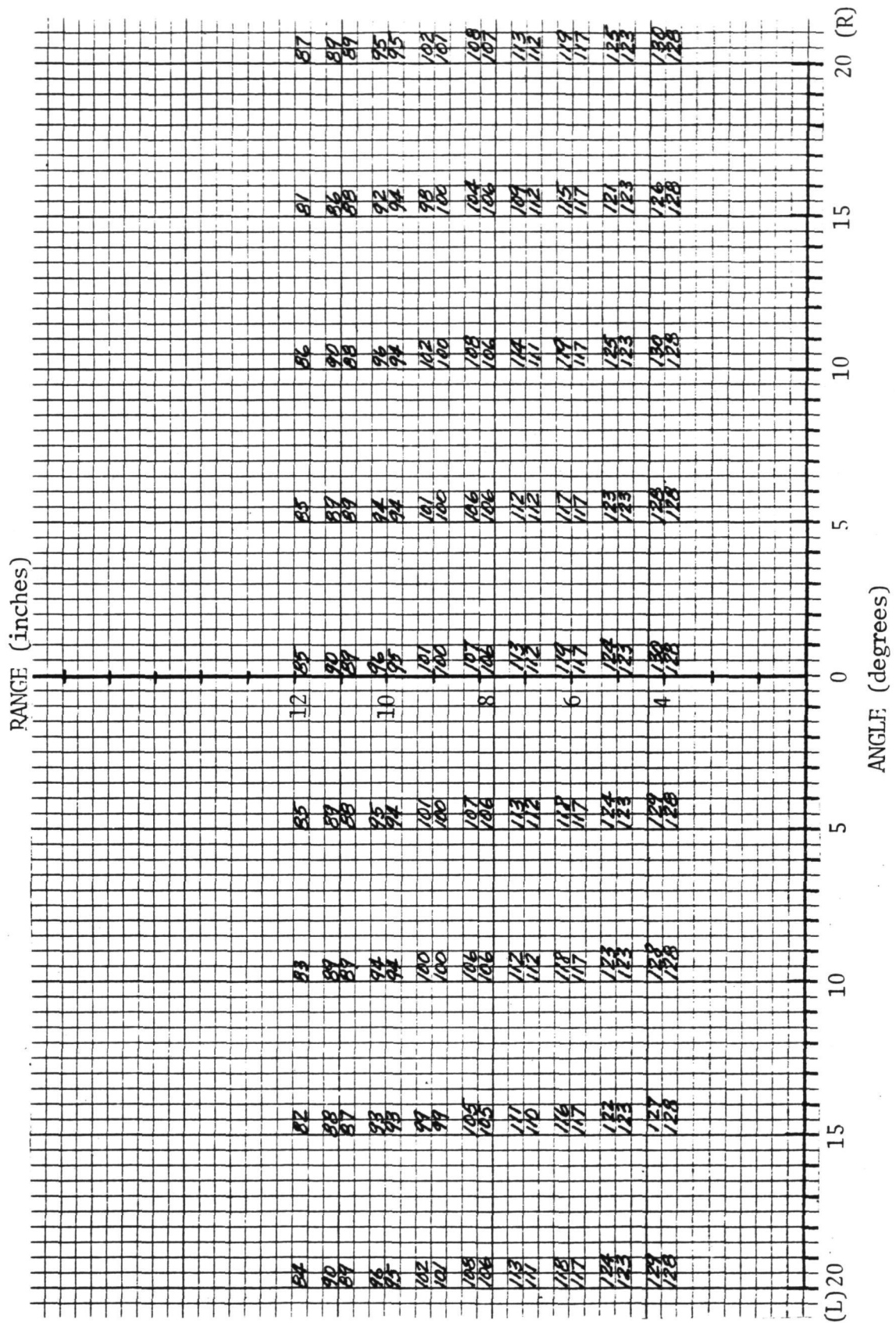


FIGURE 23. Phase-shift system response

is cumulative, once an error is developed it is carried forward. This can be seen in the sequence of counts at any point. If the two numbers differ, say by 2, that difference is continued for the rest of the run along the particular vertical line. This problem is clearly a severe shortcoming of the phase shift system.

A dynamic test result, shown in figure 24, is from a carefully arranged tracking experiment. The phase shift system output count was set to 128 when a curved metal plate was at its closest point to the transducer, figure 6. The plate was then moved in a 12 inch circular path and the resulting count converted to a filtered analog signal. A perfect result would yield a pure sinusoidal trace. This photo indicates very good tracking characteristics.

Dynamic testing with a human target was tried with the results shown in figure 25 (a) and (b). In (a) the front face was tracked roughly from 15 inches to about 27 inches (as the subject moved back and forth). Note that near the middle of the trace the smooth signal is temporarily lost. This small loss is then perpetuated into the next cycle which can be seen by the subsequent lower negative peak. The same pattern was repeated as the signal left the screen. So again, because of the cumulative nature of the method, counting errors severely handicap the system.

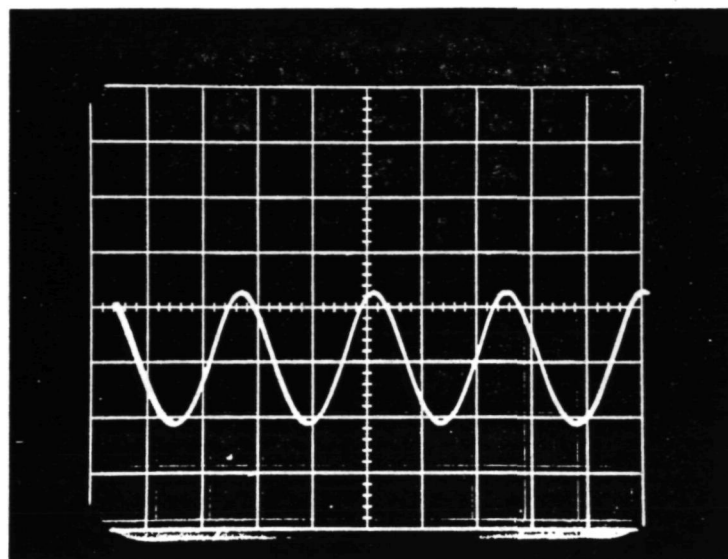
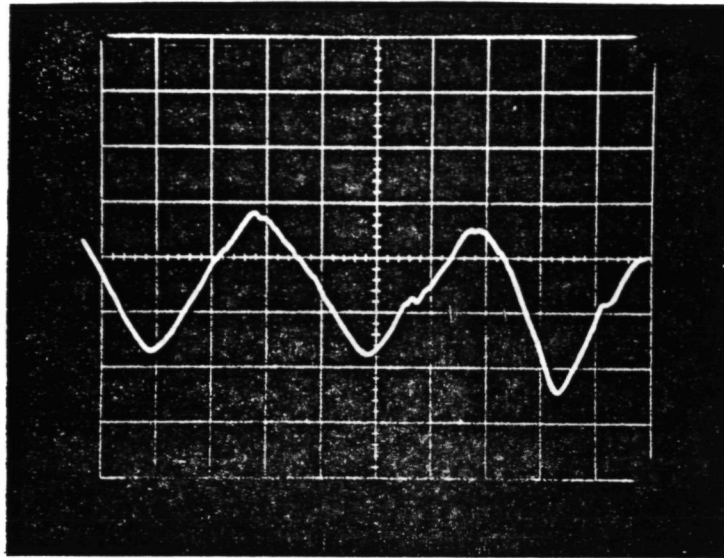
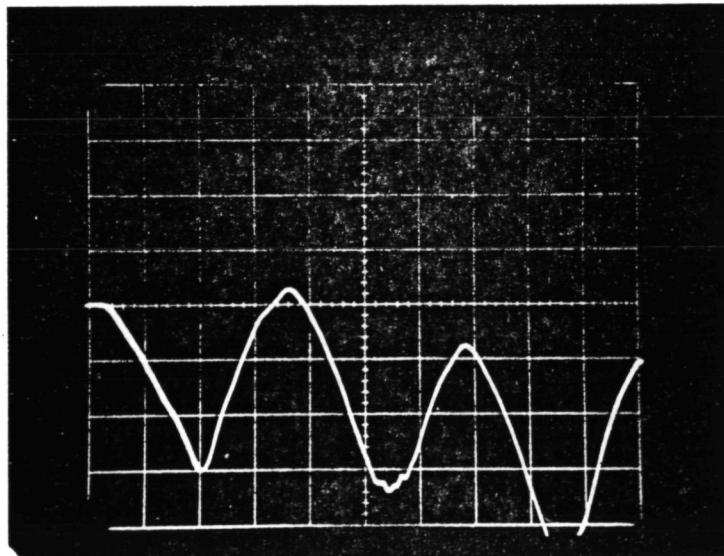


FIGURE 24. Dynamic test for the phase-shift system.

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(A)



(B)

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FIGURE 25. Phase-shift system errors.

In figure 25(b) is the same basic test except the back of the head was tracked at close range (roughly 5 to 17 inches). Like the case in (a) the cumulative errors drive the signal off the screen.

One of the possible causes for the counting error was encountered when a flat metal plate was the target in a dynamic test, see figure 26. Here as the plate approached the transducer a clear echo is received and the count is decremented every 0.2 inches. However, because of the plate angle with respect to the radial line, when the target moved away from the transducer the reflected signal is lost. Thus the count is not incremented. This produces an output signal that continuously decreases as the target approaches from the left, remains constant as the target moves away to the right, and decreases still further on the next cycle. While this extreme behavior is not like that shown in figures 25(a) and (b), the trends are similar.

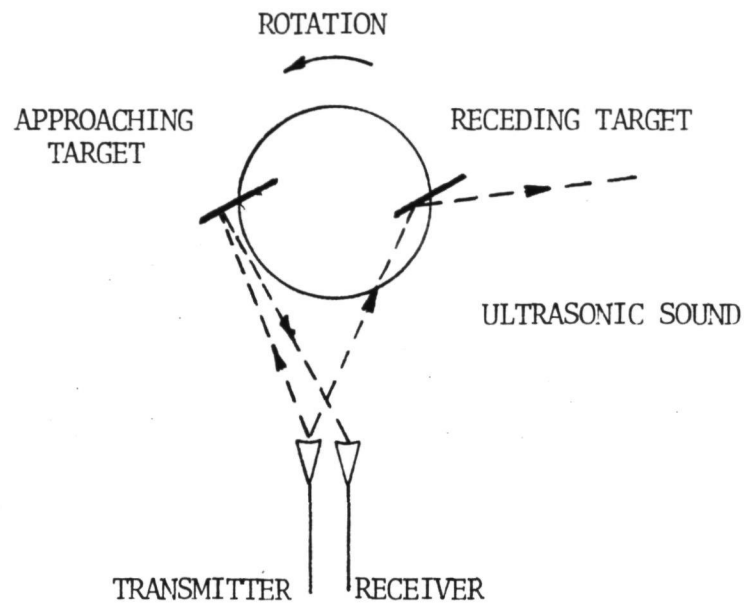


FIGURE 26. False count experiment for phase shift system.

3.2 Phase Shift System Circuits

Transmitter, figure 27

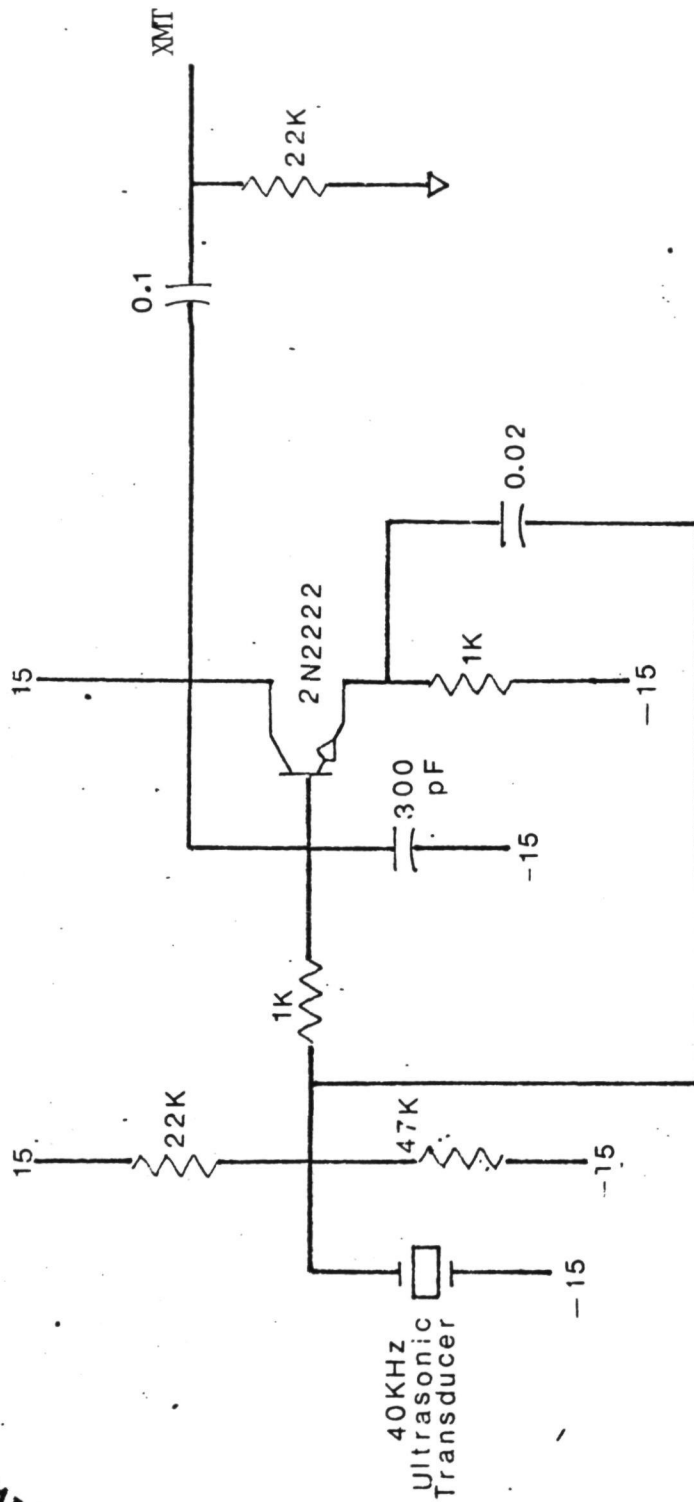
The transmitter circuit is basically a Colpitts oscillator tuned to about 40KHz with an ultrasonic piezo-electric crystal and driven 30V (peak-peak) to obtain the maximum acoustical output, consistent with the available power supply. An output signal is also capacitively coupled to a comparator on the first logic board. The transmitter and receiver share a remote power supply which allows them to be placed at any convenient location.

While other transmitter circuits were tried using an adjustable direct drive, the one shown in figure 27 is the simplest since no operator intervention is necessary. Note that in a combined echo-time--phase-shift system, to be considered later, direct drive of the ultrasonic transducer may be better.

Receiver, figure 28

A continuous echo is picked up by an ultrasonic crystal tuned to approximately the same frequency as that used in the transmitter. Crystals of the same model should be used since it was found that there is enough difference between crystals from different manufacturers (presumably all tuned to 40KHz) to cause degradation in the system performance.

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- NOTES: 1. Power supply AAK Corp., BD15.1
+15V at 100 mA. Shared with receiver board.
2. Red wire: +15V; black wire: ground;
green wire -15V; yellow wire: signal.
3. Mounted separately in transmitter wand.

FIGURE 27

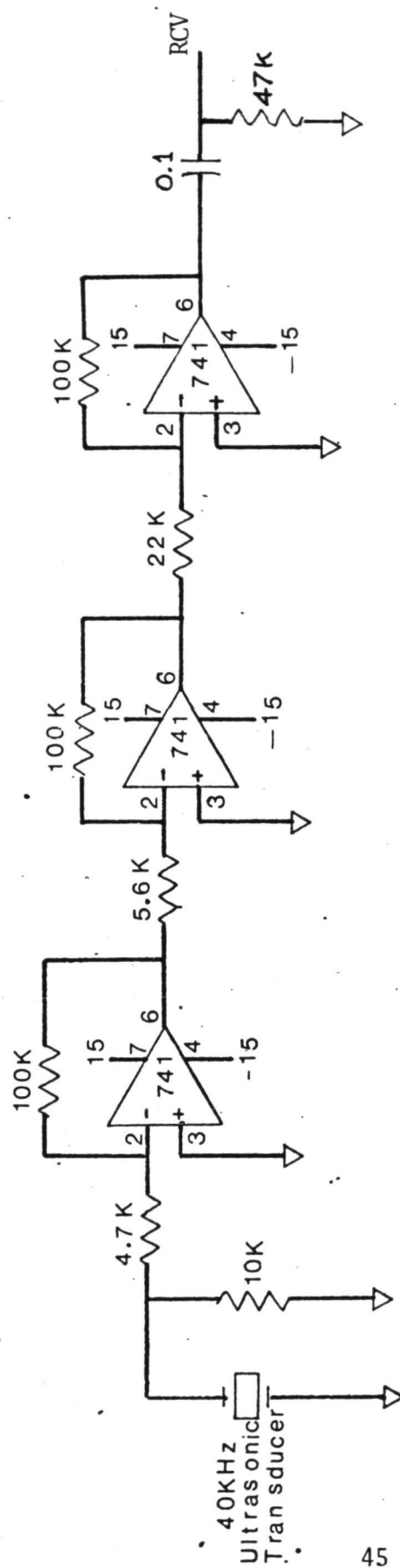
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ULTRASONIC TRANSMITTER
PHASE SHIFT SYSTEM

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- NOTES: 1. Power supply AAK Corp, BD15.1 +15V, 100 mA. Shared with transmitter board.
2. Red wire: +15V; black wire: ground; green wire: -15V; yellow wire: signal
3. Mounted separately in receiver wand.

FIGURE 28

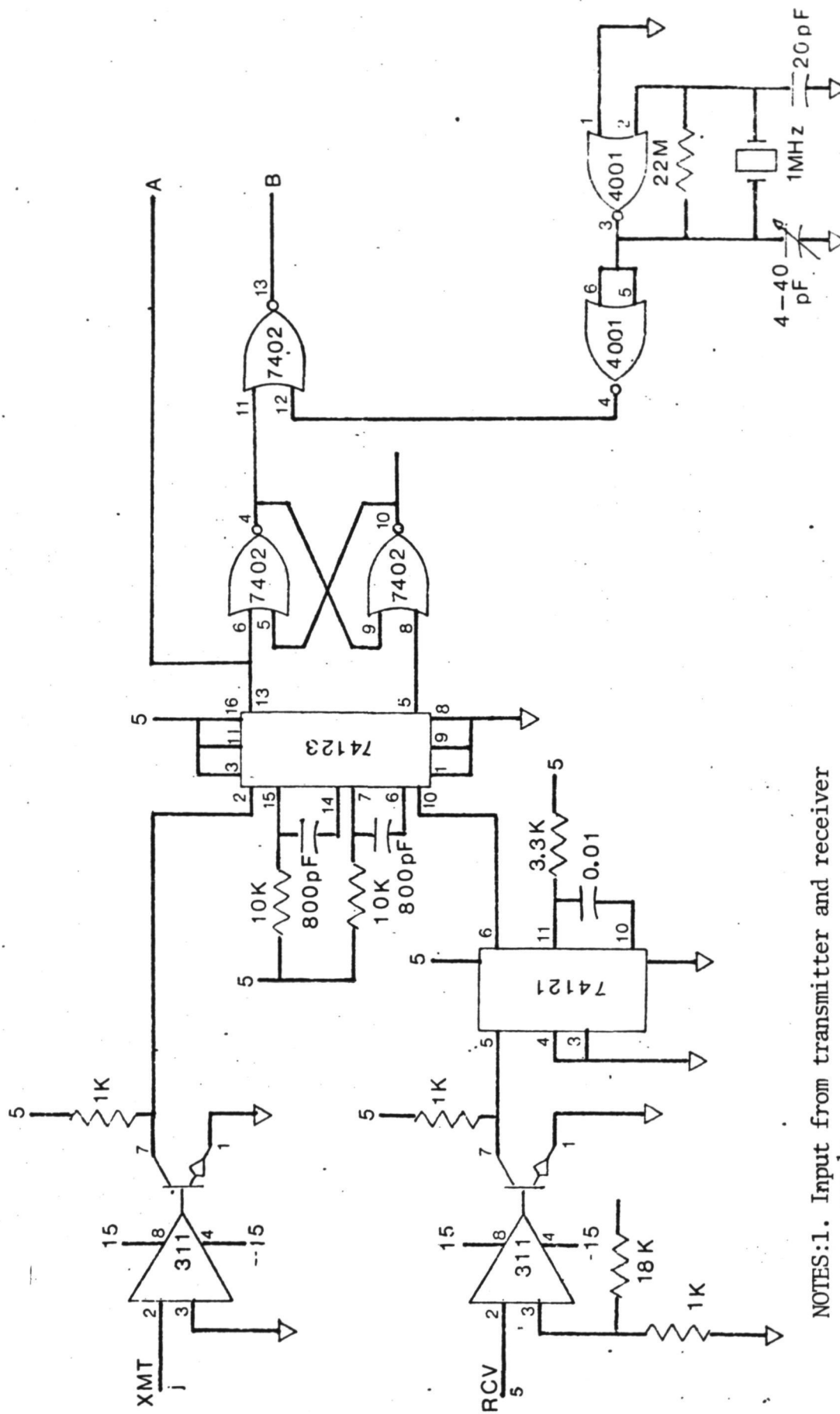
Transducer output is amplified (overall gain is about 2000) to bring it to about 1 volt peak for normal echoes. This is accomplished with three LM741's, which could easily be combined into a smaller package (an LM348 for example). To remove any DC component, the signal is finally capacitively coupled to a comparator on the first logic board.

To allow freedom of placement of the receiver, it shares a separate power supply with the transmitter.

Logic circuit 1, figure 29

The amplified echo signal is fed to an LM311 comparator slightly biased above the nominal noise level. There the 5V TTL compatible output from the 311 triggers a monostable flip-flop (74121) which outputs a pulse of 15.0 μ sec. This is done to insure that no false triggering of the 74123 will occur. During the design stage it was found that when weak echoes were received distortion and false triggering occurred when the sine wave was about to enter its negative half cycle. By insuring that the comparator/monostable output stays high into this negative phase the problem is eliminated.

Positive going signals from the transmitter LM311 and the receiver 74121 trigger the two one shots in the 74123. This produces two short pulses separated by the phase difference between the transmit and receive sinusoids.



NOTES: 1. Input from transmitter and receiver wands.

2. Circuit continues on second page

3. Power supply, AAK Corp., MT152-1

4. Mounted on vector board

5. Edge connector pin no. shown

FIGURE 29

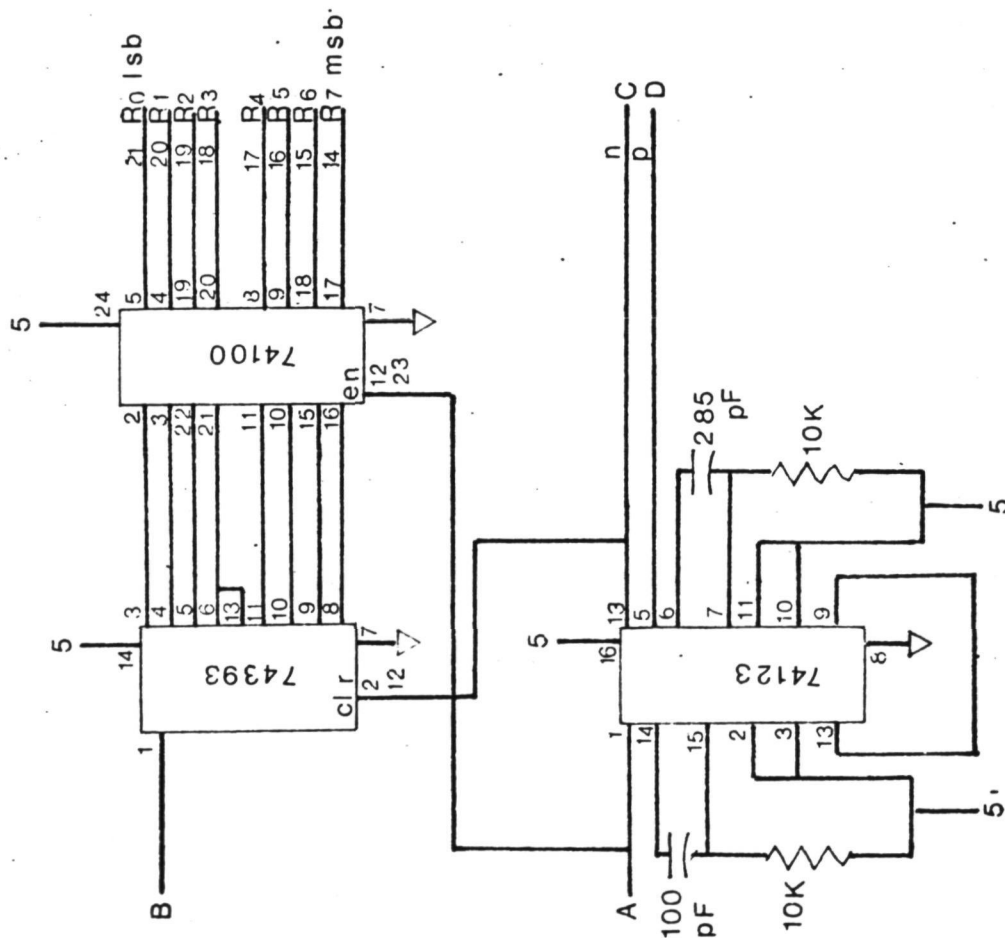
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ULTRASONIC RANGING
PHASE SHIFT LOGIC BOARD 1

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FIGURE 29 CONT.

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ULTRASONIC RANGING
PHASE SHIFT LOGIC BOARD 1

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These pulses set and reset an SR flip flop (7402) the output of which gates (7402) a 1MHz clock. The clock uses a crystal controlled CMOS 4001 circuit. The SET pulse from the 74123 is also used to latch the phase count into the 74100 and trigger another 74123 which in turn produces other timing pulses.

The gated clock signal is fed to a 74393 counter giving an 8 bit parallel output. The counter is cleared with a pulse from the 74123 just after the count is latched into the 74100.

A \pm 15V and 5V power supply is needed for logic circuit 1 and 2.

Logic Circuit 2, figure 30

The 8 bit phase count from the 74100 latch is next input to 2 pairs of 7485 comparators. The count, C(N), is matched against fixed HI and LOW values provided by two 8 bit DIP switches. If C(N) is greater than HI, the top 7485's (pin 5) goes high; similarly if C(N) is less than LOW, the bottom 7485's (pin 7) goes high.

These conditions are stored in a 7474 D flip flop with a timing pulse from one of the 74123. The D output will be used in the logic circuit to provide the phase count status for the previous phase measurement.

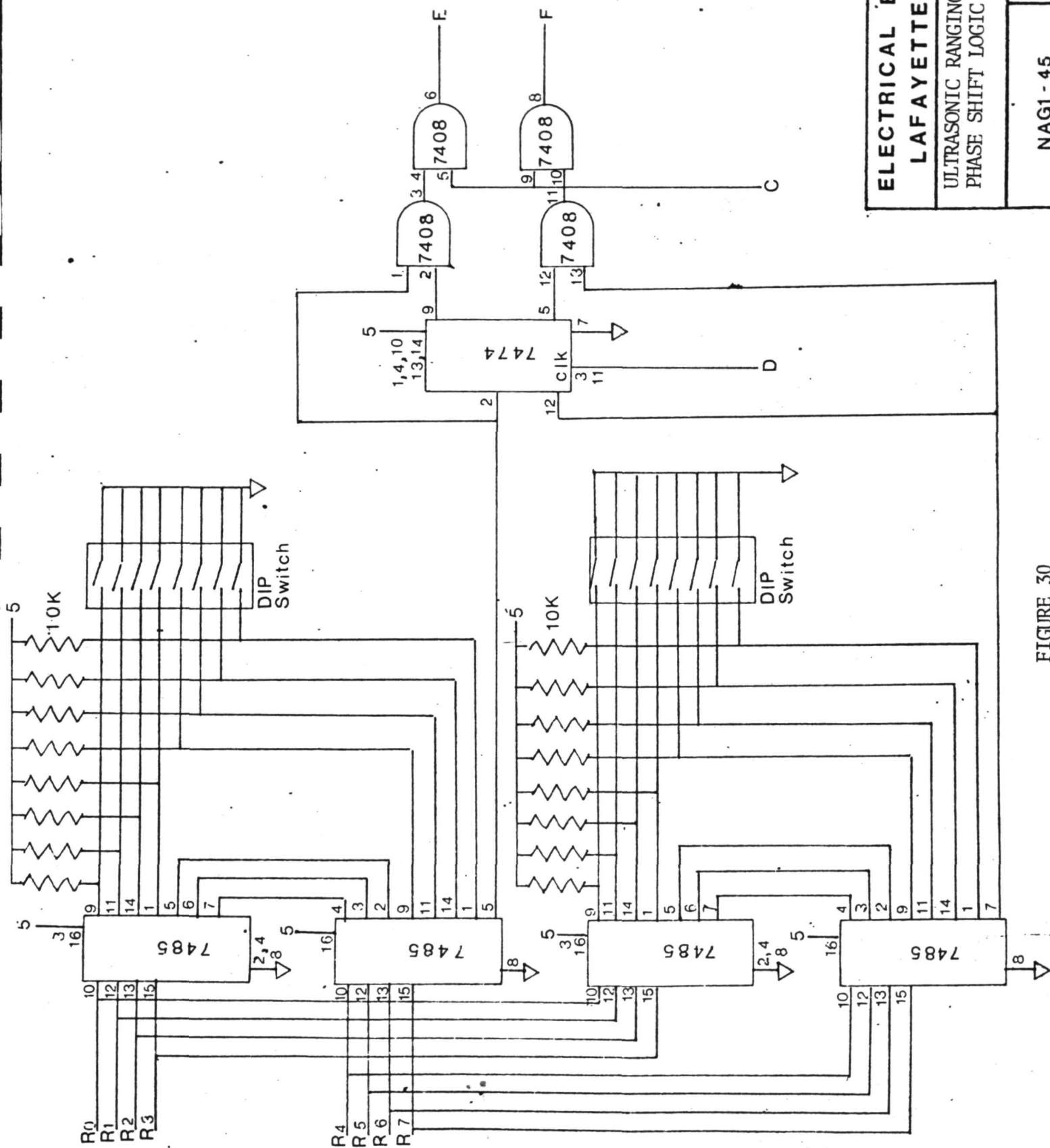


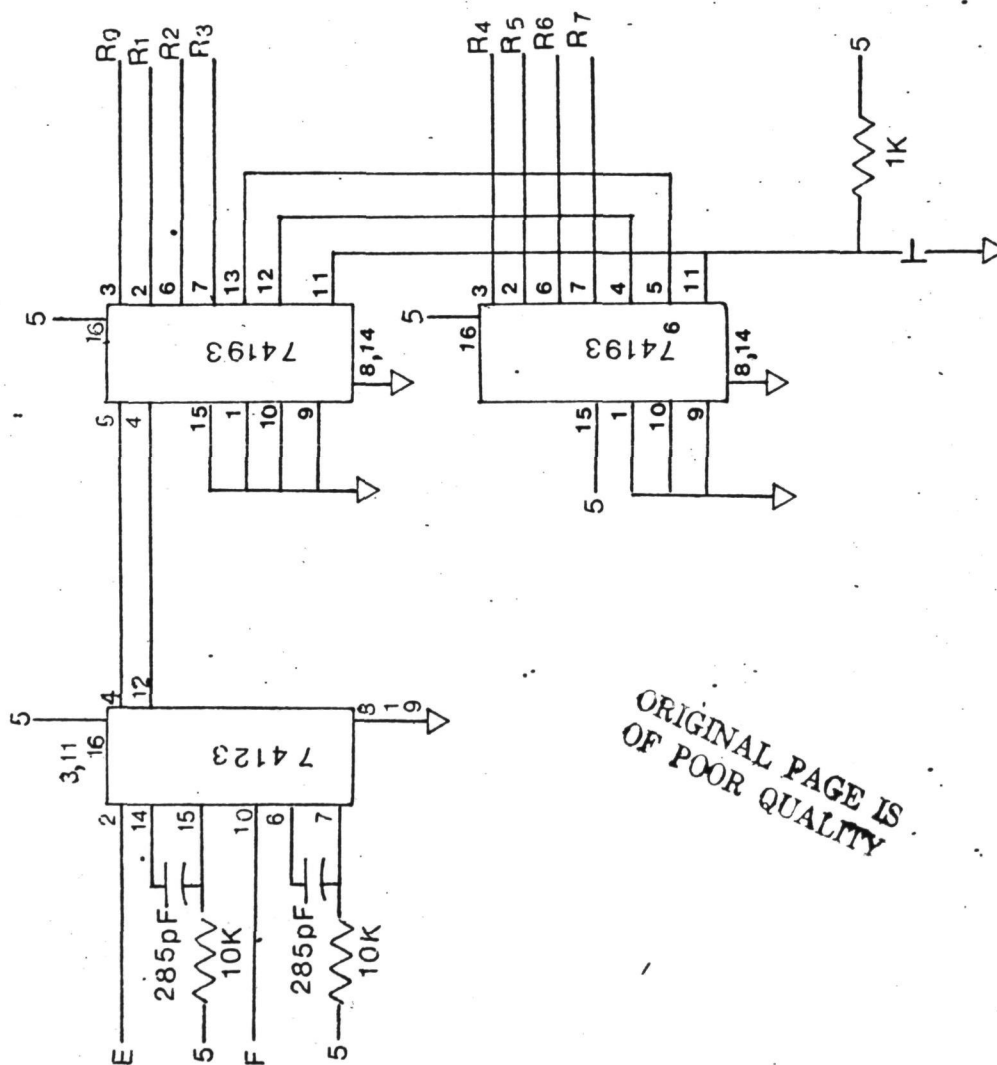
FIGURE 30

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ULTRASONIC RANGING
PHASE SHIFT LOGIC BOARD 2

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- NOTES: 1. Input from logic board 1
2. Circuit continues on second page
3. Power supply, AAK Corp., MT152-1
4. Mounted on vector board
5. Edge connector pin no. shown

FIGURE 30 CONT.

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ULTRASONIC RANGING
PHASE SHIFT LOGIC BOARD 2

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In the meantime output from the comparators (current phase status) and the D output is used to logically provide up/down pulses to the 8 bit up/down counter (74193's).

Conditions for UP count are

$$C(N) < \text{LOW AND } C(N-1) > \text{HIGH}$$

for down count

$$C(N) > \text{HIGH AND } C(N-1) < \text{LOW}$$

The pulse is actually the same one that clears the 74393 counter. The final 74123 provides the separate signals to the 74193 (note that pins 4 and 5 of the counter must be high for proper operation).

A reset circuit is provided to initialize the output counter to 128 when desired.

Figure 31 is the edge connector and 16 pin DIP cable map.

POWER STRIP
+5
GD
+15
-15

LOGIC 1	
EDGE CONNECTOR	
1	+5
2	
3	+15
4	-15
5	RCV
6	
7	
8	
9	XMT
10	
11	
12	
13	CNT
14	R ₁ ' D
15	R ₆ '
16	R ₅ '
17	R ₄ '
18	R ₃ '
19	R ₂ '
20	R ₁ '
21	R ₀ '
22	GD

LOGIC 2	
EDGE CONNECTOR	
1	+5
2	R ₀ '
3	R ₁ '
4	R ₂ '
5	R ₃ '
6	R ₄ '
7	R ₅ '
8	R ₆ '
9	R ₇ '
10	
11	
12	
13	CNT
14	R ₇ D
15	R ₆
16	R ₅
17	R ₄
18	R ₃
19	R ₂
20	R ₁
21	R ₀
22	GD

DIP CABLE CONNECTIONS	
1	R ₁ R ₀ 16
2	R ₃ R ₂ 15
3	R ₅ R ₄ 14
4	R ₇ R ₆ 13
5	+5 12
6	GD +5 11
7	+5 10
8	
9	

FIGURE 31

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PHASE-SHIFT SYSTEM BOARD CONNECTIONS	
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3.3 Phase Shift System Signals

The top trace in figure 32 shows the signal driving the ultrasonic piezoelectric transducer. The bottom trace is the amplified echo signal. The difference between the positively going zero crossings of these two waves is defined as the phase shift with the transmitted wave always starting the measuring sequence.

In figure 33 (bottom) is the SR flip flop output which determines the phase difference. The top trace is the resulting count which is latched and compared. Two cycles are shown, the left most being $C(N-1)$ and the one to the right $C(N)$. In the case shown $C(N) = C(N-1)$ so the target has not changed.

No other signals are shown since from this point on all signals are transient, only appearing when definite movement is detected.

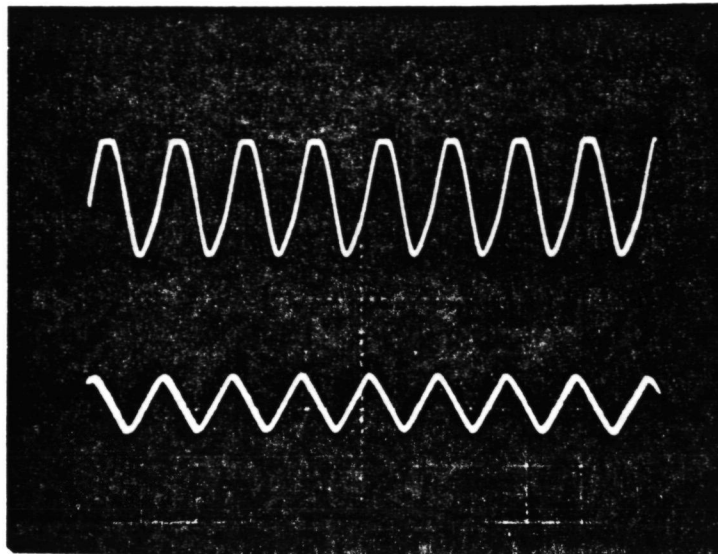


FIGURE 32. Phase shift system signals.

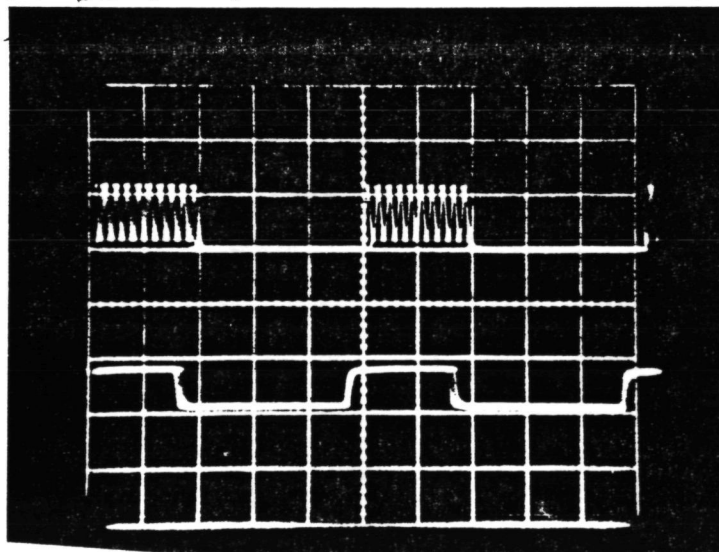


FIGURE 33. Phase shift system signals.

3.4 Complete System

The complete system with a wire wrapped circuit on a plug board is shown in Figure 34. Note the two transmit and receive wands.

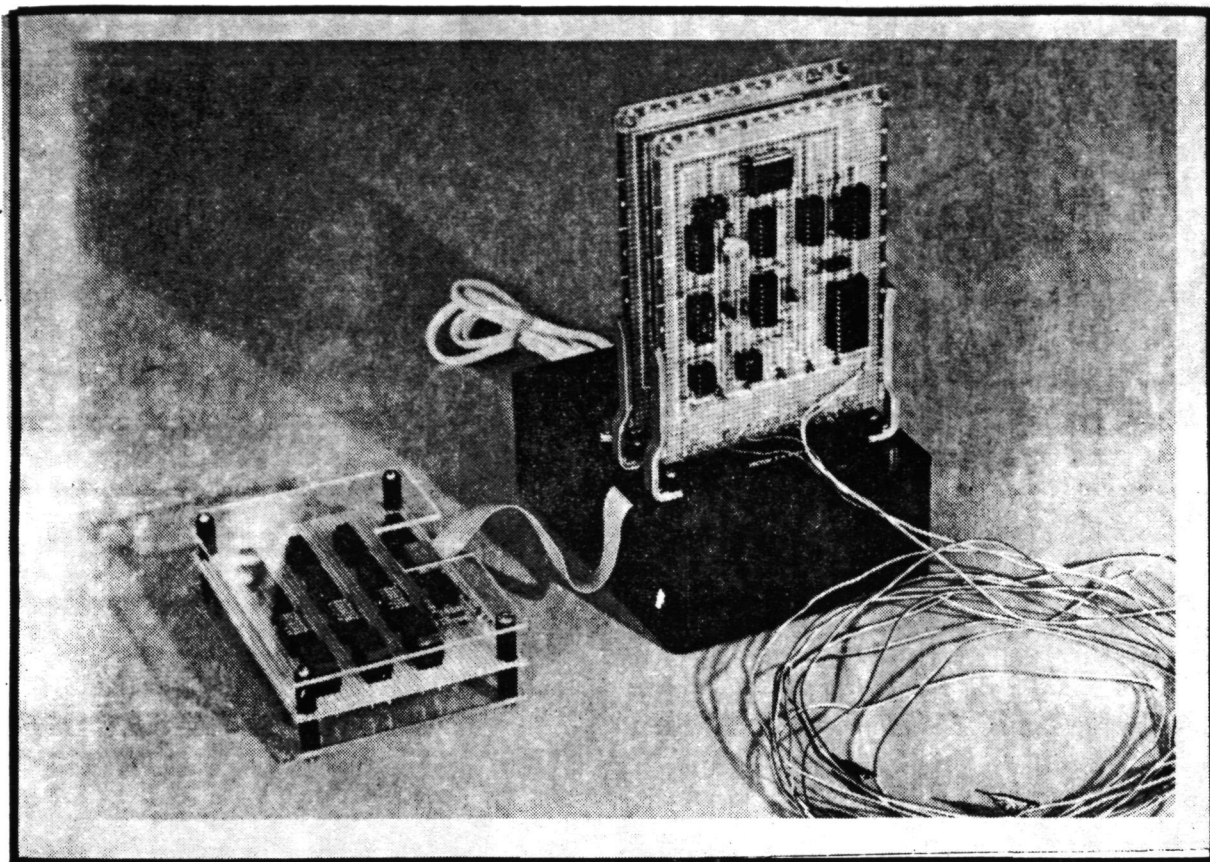


FIGURE 34 (A) Phase shift system construction. Note long leads to Rcv/Xmt wands. Small board is for digital output.

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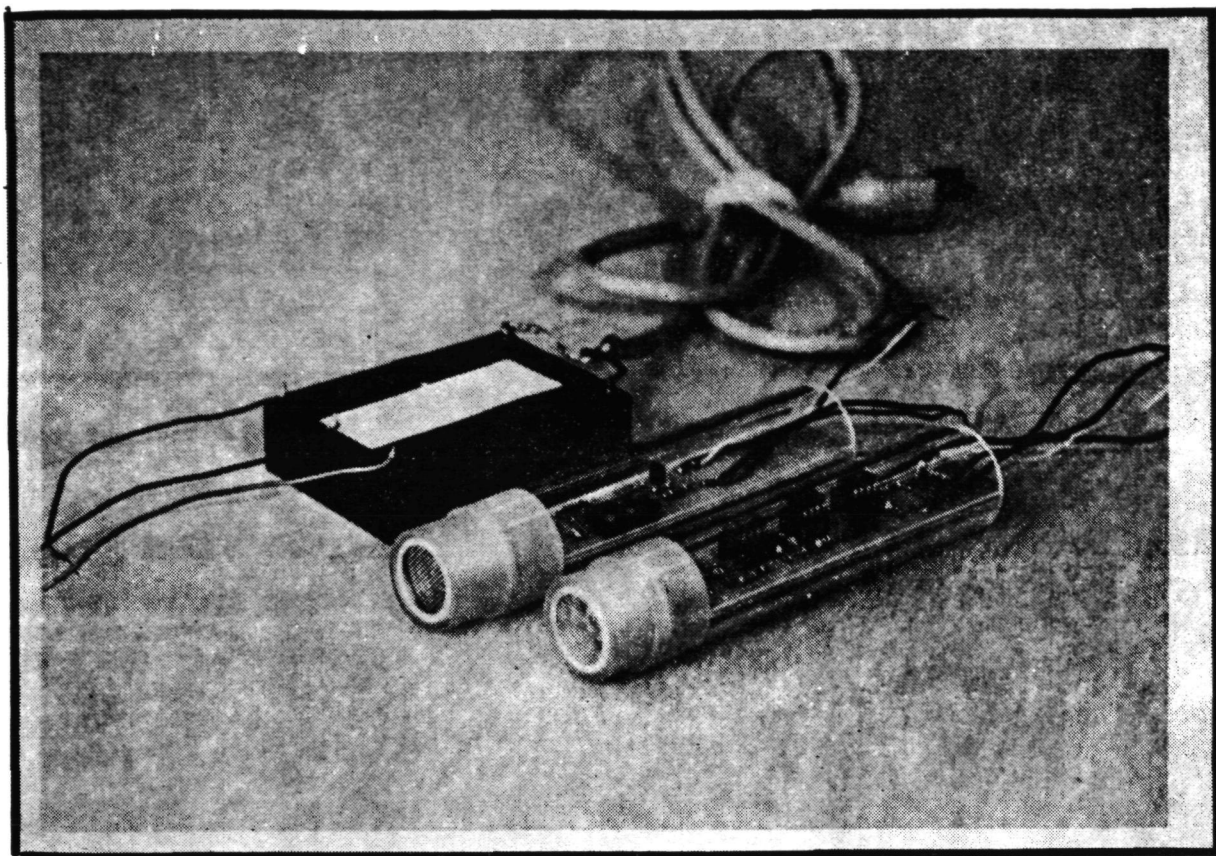


FIGURE 34 (B) Phase shift system
Rcv and Xmt wands.
Separate power supply.

3.5 Direct Phase Measurement

Direct phase measurement was attempted with a 565 Phase Locked Loop chip which has a loop that can be broken, figure 35. The signal from the transmit circuit was fed to the normal input, while the received signal was fed to the pin normally leading from the VCO. The output is a signal whose magnitude depends on the phase difference between these two signals. However, output corresponds only to an absolute value phase shift spanning just 180° .

In figure 36 a circuit to span a 360° phase shift is shown which was also tested. It utilized a pair of T flip flops and an XOR. The average output covered a 5V range but was sluggish due to the filter.

Neither of these approaches proved acceptable since the transfer characteristics are continuous over the operating range. Thus one could not tell whether the phase was decreasing or increasing by measuring the output voltage. Since this information is necessary to track the target, the direct method was set aside for another approach.

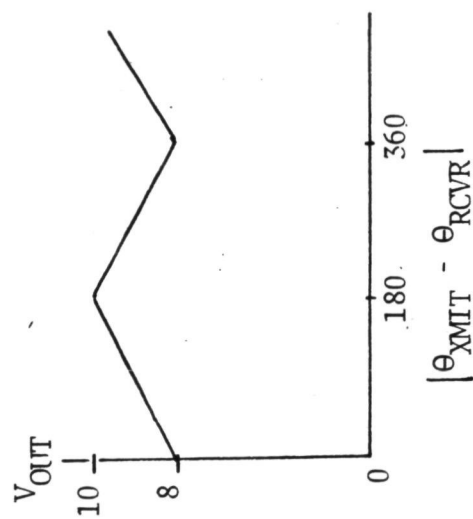
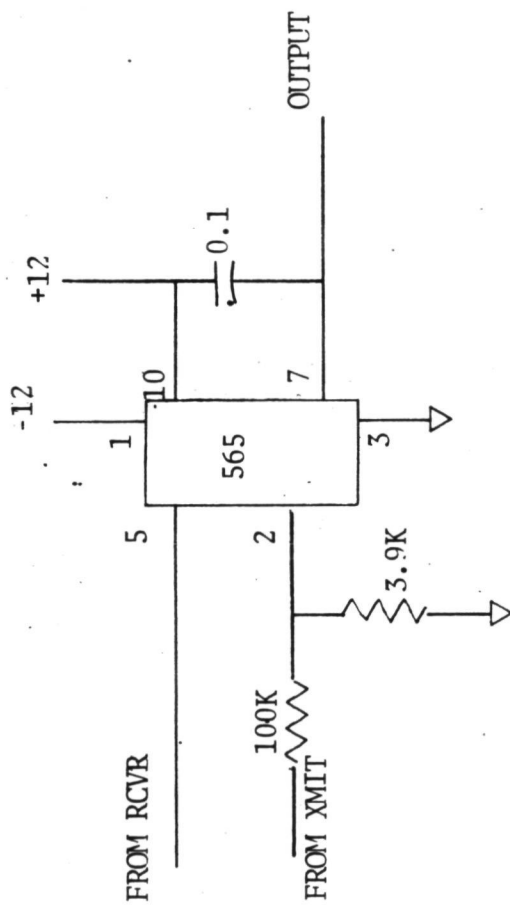


FIGURE 35

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DIRECT PHASE MEASUREMENT

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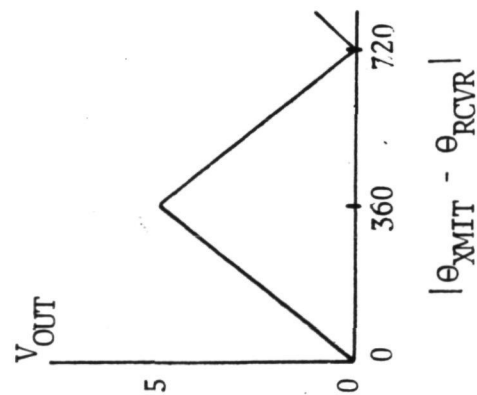
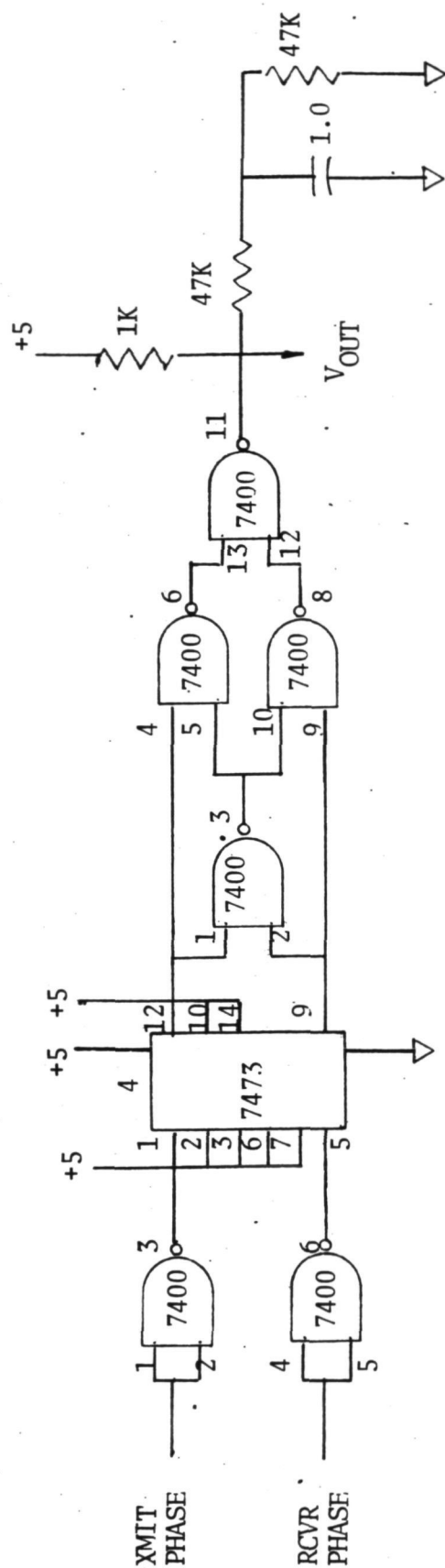


FIGURE 36

3.6 Microprocessor System

Using the transmit and receive signals to control an SR flip flop, a count can be generated for consecutive phase shift measurements exactly as was done in the wired logic circuit. Call these counts $C(N-1)$ and $C(N)$ with the corresponding counting times T_1 and T_2 . Four possible conditions can occur, see figure 37. In the first two, 1 and 2, the phase time and count will gradually increase or decrease as the target respectively moves away from or closer to the detector. In the second two conditions, 3 and 4, the count makes a drastic change as the phase shift crosses the 0° point. In case 3 the count, $C(N)$, will increase, but the target is actually coming closer. This is an opposite count direction than that for case 2 in spite of the fact the target is moving in the same direction. A corresponding phenomena occurs when the target moves away and the count makes a drastic negative change, case 4.

If it is assumed that the head moves at velocities much slower than the speed of sound, then an upper bound, MAX, in the count change,

$$\Delta(N) = C(N) - C(N-1),$$

can be used to determine when a 0° phase shift crossing has occurred.

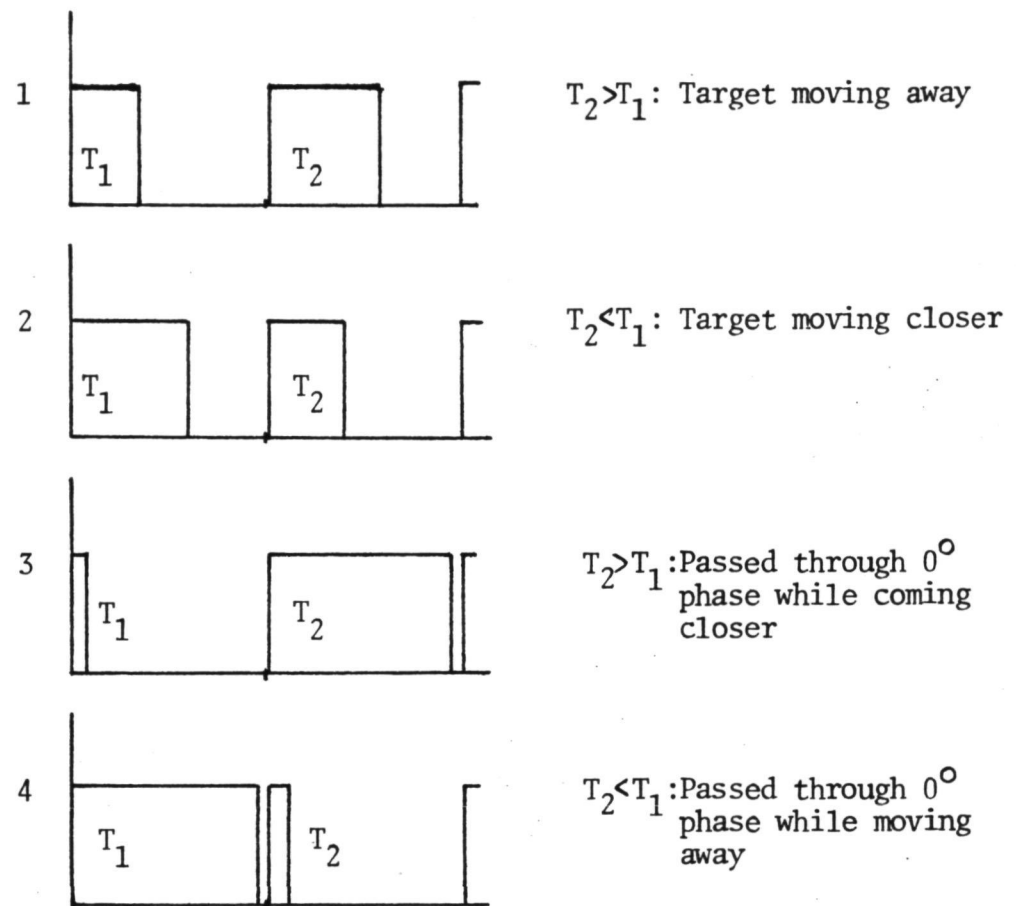


FIGURE 37 Phase shifting patterns

Using the above logic (see flow chart in figure 38) a count corresponding to the accumulated phase shift can be generated with the program given below. The program was written on an MC6800 system and successfully tested, but it is too long to process the phase information every 25 μ sec. To continue development of a microprocessor based system, two variations to the microprocessor system are now being investigated. First, a faster (11 MHz) processor (Intel's 8039) is being studied. Secondly, a program that only counts changes in integral wavelengths is being developed. This latter approach is the same as that used in the wired logic system.

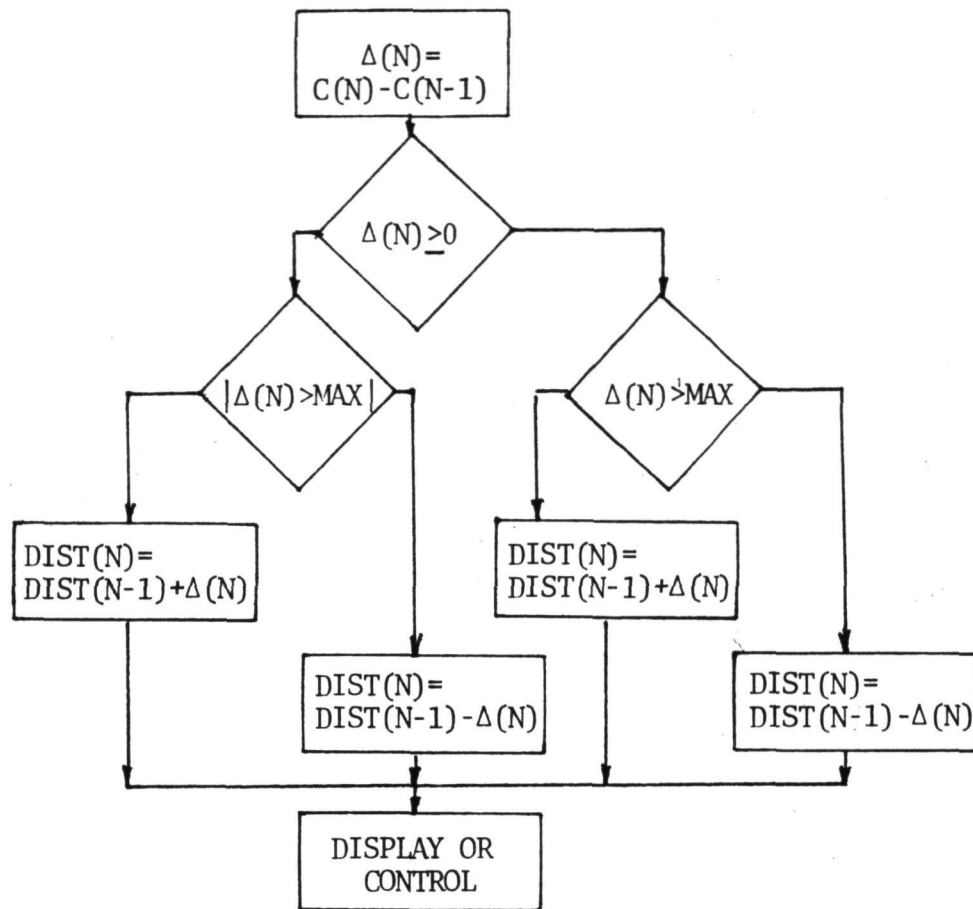


FIGURE 38 Flow chart for phase tracking

IV. SYSTEM COUPLING

With some minor adjustments it is possible to couple the echo-time and phase shift systems. This is done at the UP/DOWN 74193 counter on the phase-shift logic 2 circuit board, figure 39. Instead of the present button, the enable latch pulse for the 74100 in the logic circuit for the echo time system is connected to the counter LOAD (pin 11). The 3 bit latch output from the echo time system is also connected directly to the 8 bit presetting inputs on the counter. Then, whenever the echo-time system has a valid measurement, the 74193 counter will be updated. Between these updates, the phase shift system will track small variations (0.2 inches) in target distance.

This arrangement will eliminate the error propagation in the phase shift system since the distance will be

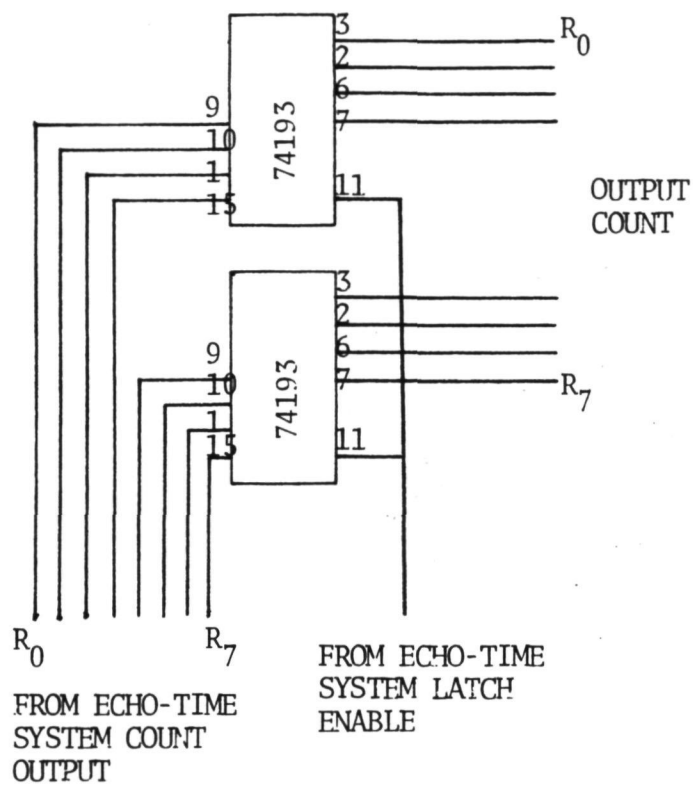


FIGURE 39. Phase-shift system modification for combined operation.

updated periodically (about every $1/60$ sec.) by the echo-time method. However, since the echo time system is inherently less accurate than the phase shift method, the combined system may have precision without accuracy.

Two minor adjustments are necessary to make this approach work. First, the ultrasonic frequency of one of the systems must be changed so that the two systems do not interfere. Secondly, the clock frequency of the echo-time system must be adjusted so that its count corresponds to the same distance as the phase shift method.

V. POLAROID ULTRASONIC RANGING SYSTEM

The ultrasonic ranging system (7) manufactured by Polaroid Corp. for their sonar cameras and available in experimenter's kit form was also studied in some detail. With some modifications, its principle of operation is identical to the echo time system (section 2). The system was evaluated with various targets, the flat metal plate again providing the best results. Because of the consistent accuracy of this system various attempts were made to spread the transducer's radiation pattern. These are also discussed. Finally some ideas which might make the system adaptable to the oculometer specifications are suggested.

5.1 System Operation

The Polaroid system operates by measuring the time between a complex transmitted wave and the returned echo. An output, sequentially composed of a few cycles of 60, 57, 53 and 50 KHz, starts the timer. When the echo is returned, timing stops. This method was chosen to reduce echo interference and cancellations; since, while one frequency may not be returned, it is unlikely that all will be nulled. Also to enhance their system, the gain of the receiver is increased as a function of time; thus providing approximately a constant output even for far away targets. Tuning of the amplifiers is also sharpend and slightly changed as a function of time to "bring in" distant objects.

Figures 40 to 44 show the results of the evaluation study of this system. The experiment is identical to the static tests performed on the echo-time and phase shift systems. The ultrasonic transducer always faced perpendicular to the zero degree line and the target was always aligned perpendicular to the respective radial lines. Four conditions were used: (1) a flat metal plate 6"x12.75" (this will be considered the bench mark data); (2) a Sytrofoam dummy head aimed at the left and right eye;

(3) a human subject and (4) a human subject with range measurement taken from the back of the head.

The results are displayed differently since the output from Polaroid's system provides distance measured to tenths of a foot from 0.9 to 35 feet. The dark lines graphically represent errors, while the numbers give the quantitative error in tenths of feet. Errors less than 0.1 are considered good for this system.

Analysis of the data in figure 40 for the flat metal plate, the best possible target, shows good accuracy within a $\pm 5^{\circ}$ arc. However, when outside this boundary at long range, the error can increase beyond acceptable limits. The Styrofoam dummy head results, figures 41 and 42, are worse except along the 0° radial line. This is not surprising since the Polaroid system is designed to focus on an object directly in front of the camera. When used on a human head, figures 43 and 44, the errors become totally unacceptable.

In an effort to broaden the radiation pattern of Polaroid's ultrasonic transducer, various enclosures were used but none increased the width by more than a few degrees. First corner reflectors with 180° (flat), 150° , 120° , and 90° inside angles were tried. A dummy head located 3'

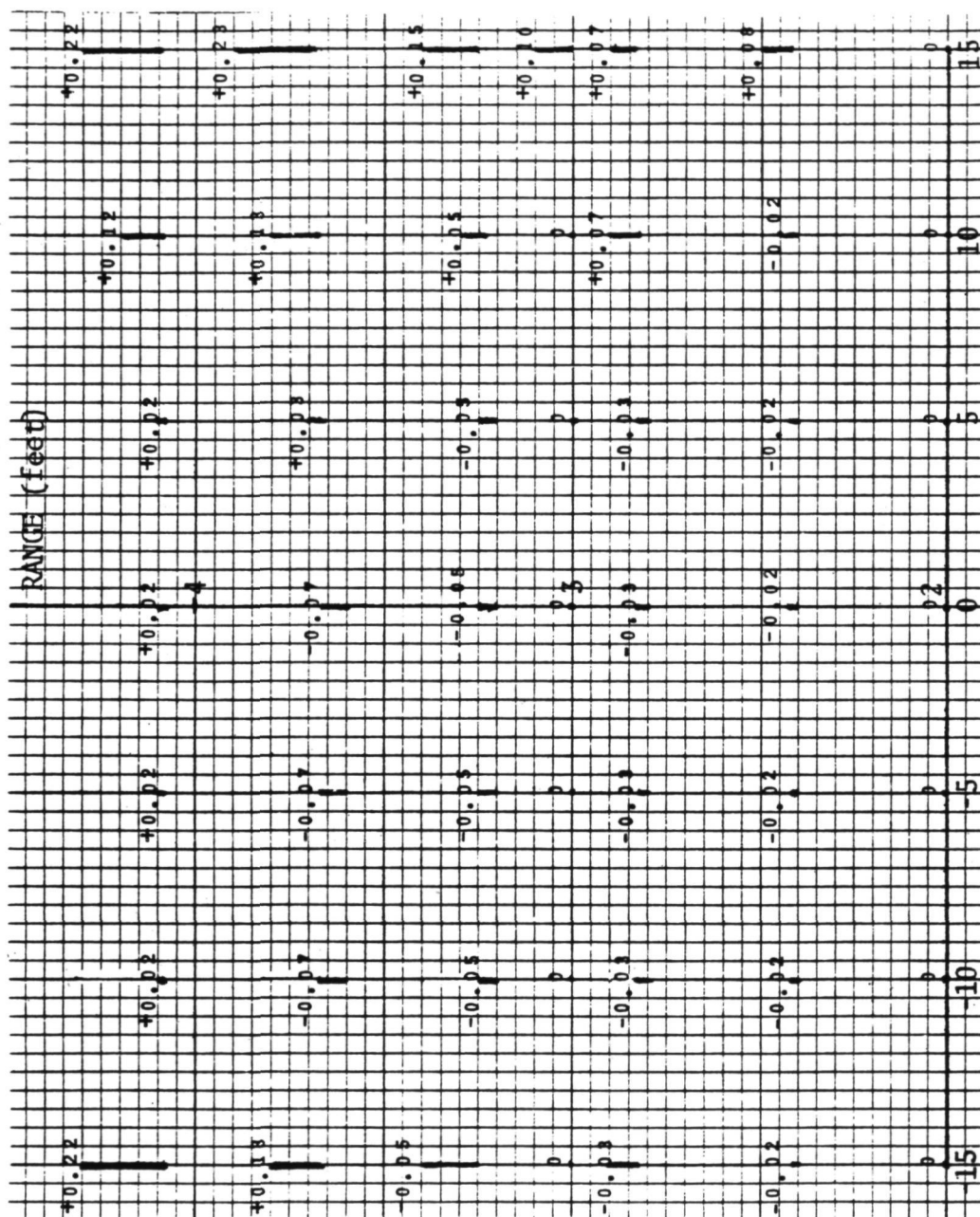


FIGURE 40. Polaroid system static performance (flat plate)

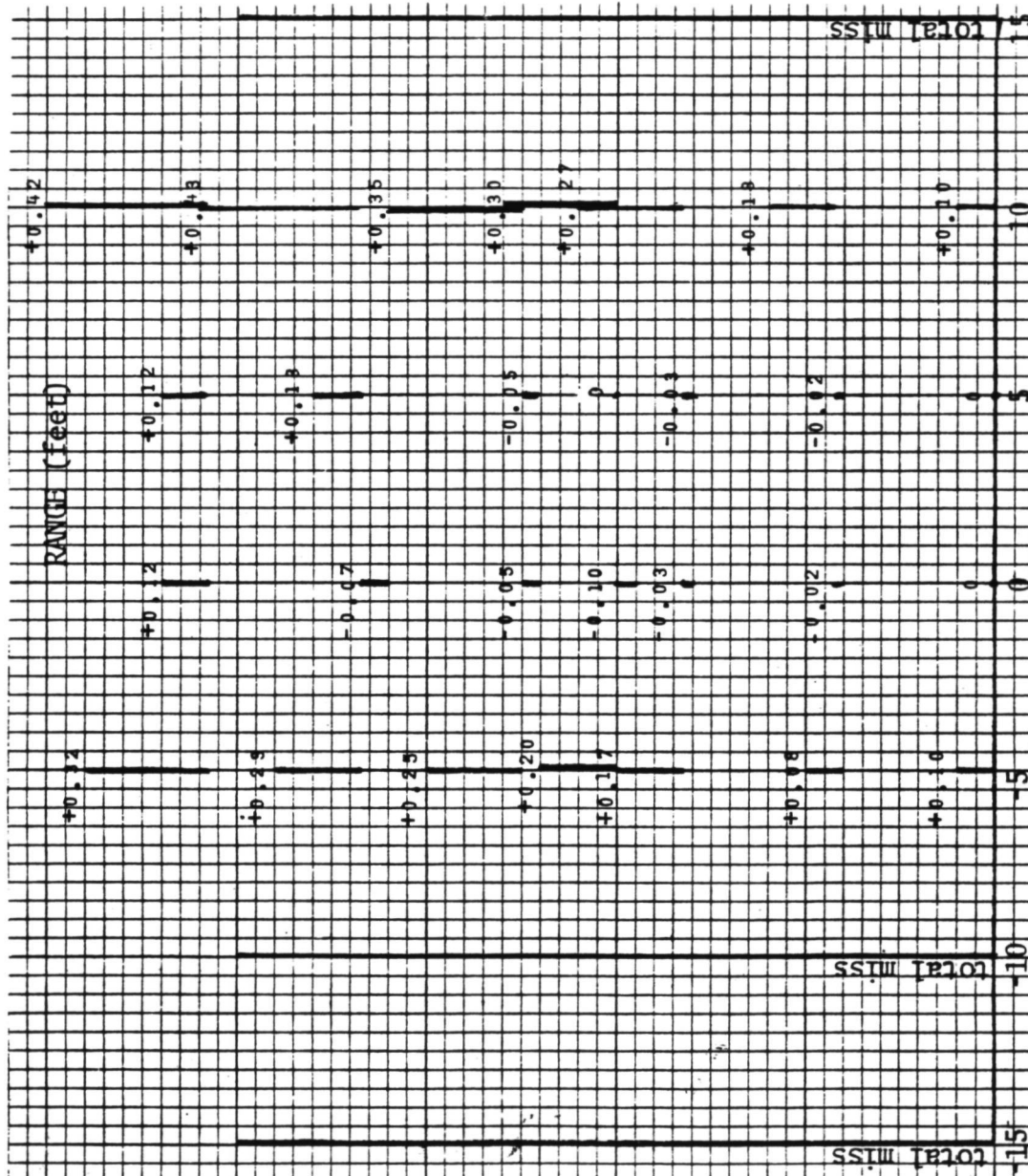


FIGURE 41. Polaroid static performance
(dummy head - left eye)

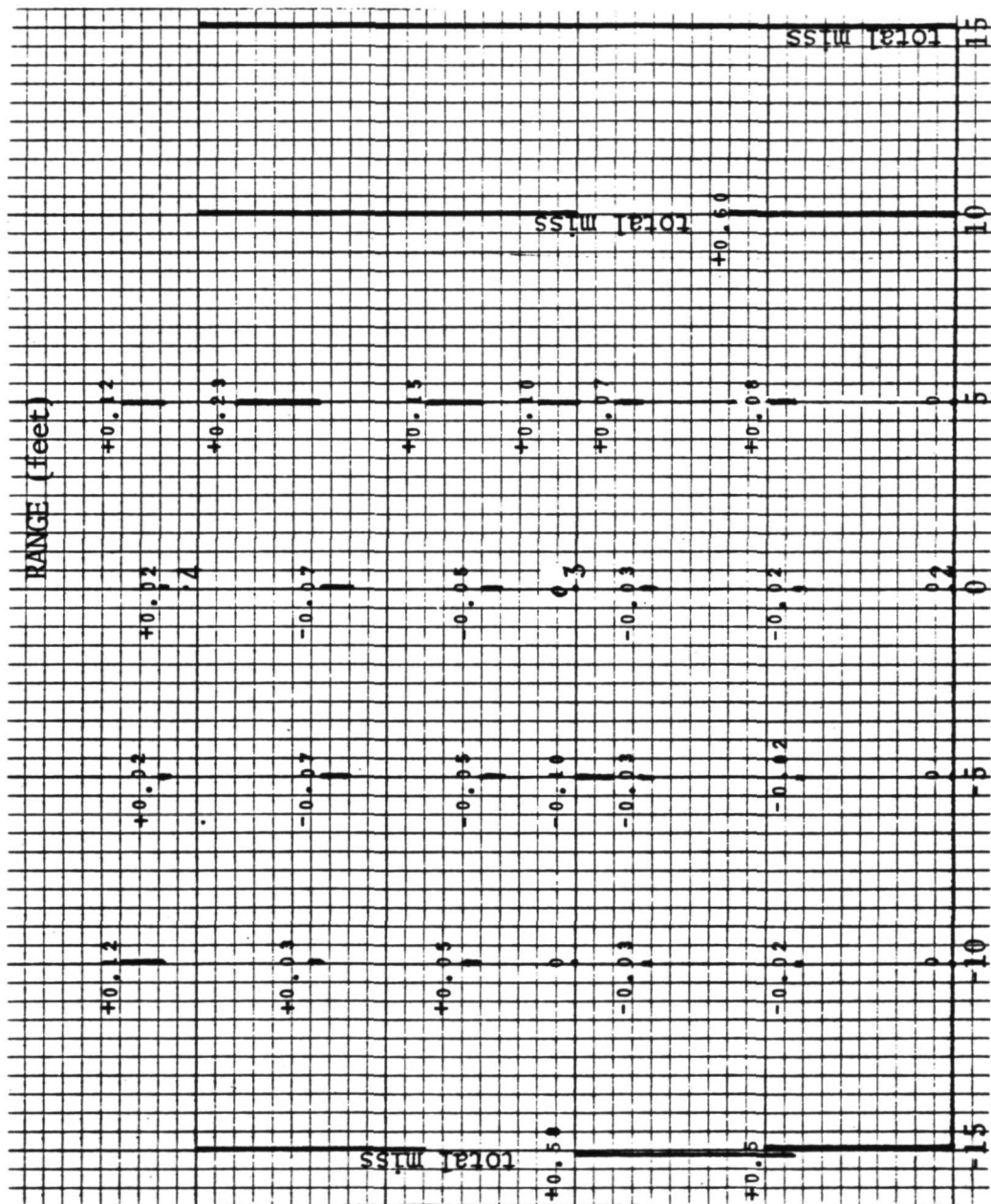


FIGURE 42 Polaroid static performance
(dummy head - right eye)

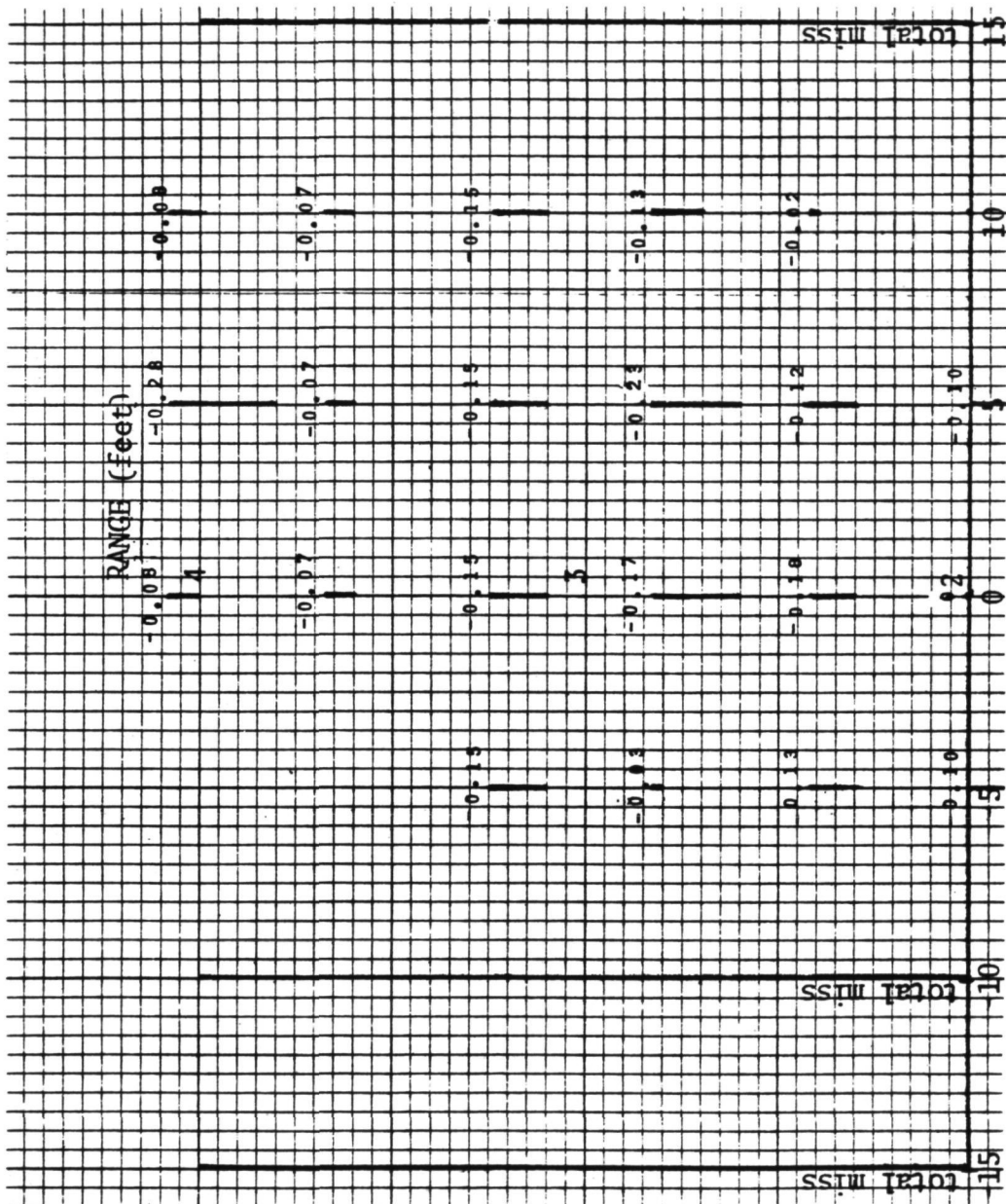


FIGURE 43 Polaroid static performance
(human head - frontal)

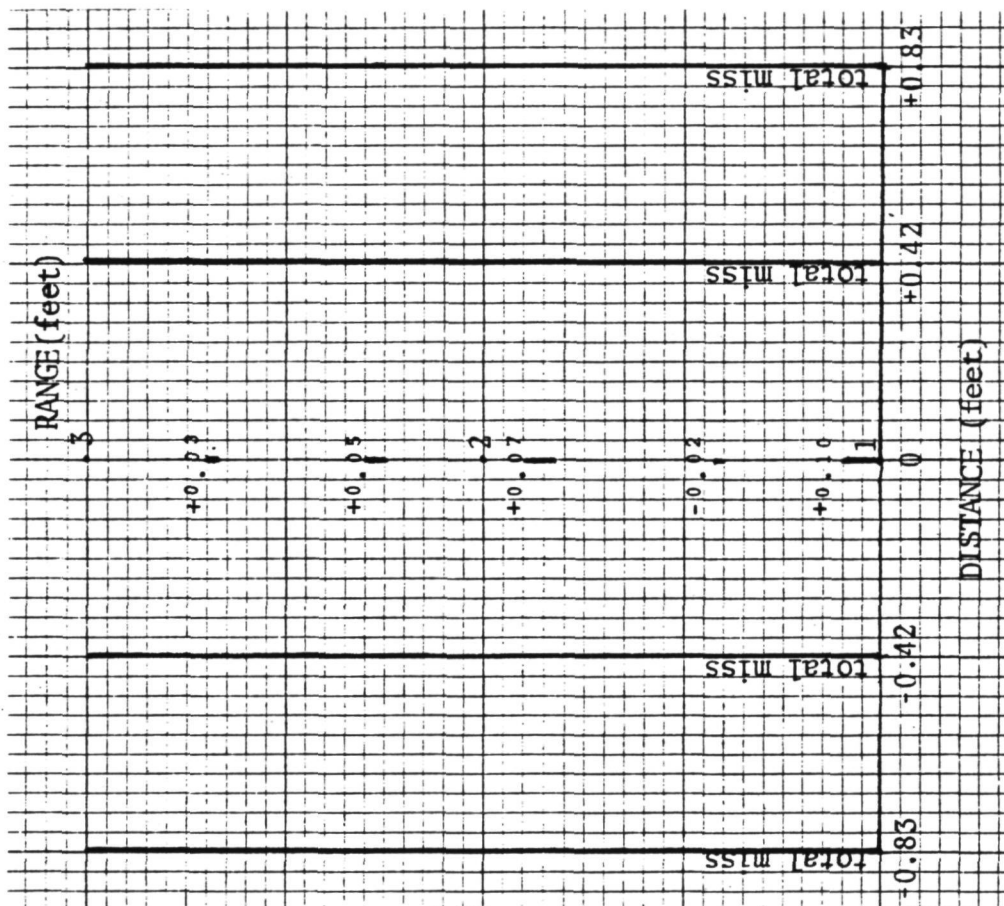


FIGURE 44 Polaroid static performance
(human head - back)

from the transducer was moved through an arc until the error in range exceeded 0.1'. Within these left and right boundaries good range data can be obtained. The total angular span at 3' ranged from 14° with a 180° corner to 17° with a 90° corner. Since at 17° this is only a 9" coverage, the system cannot accurately track over the required 12" field. Other transducer systems with parabolic reflectors, both aperture and horn fed, produced no improvements.

5.2 System Modification

It may be possible to use Polaroid's system, figure 45, if certain modifications can be made without jeopardizing response time or accuracy. First by employing two transducers with overlapping beams a wider area could be tracked. Or as an alternative, a single transducer could be mechanically oscillated in a small arc. On the one hand a high voltage (600V) switch would be needed, while for the other approach a cumbersome mechanical system would be required. Neither method is impossible and will be further investigated.

If this modification proves feasible and it is possible to incorporate the Polaroid front end to the logic

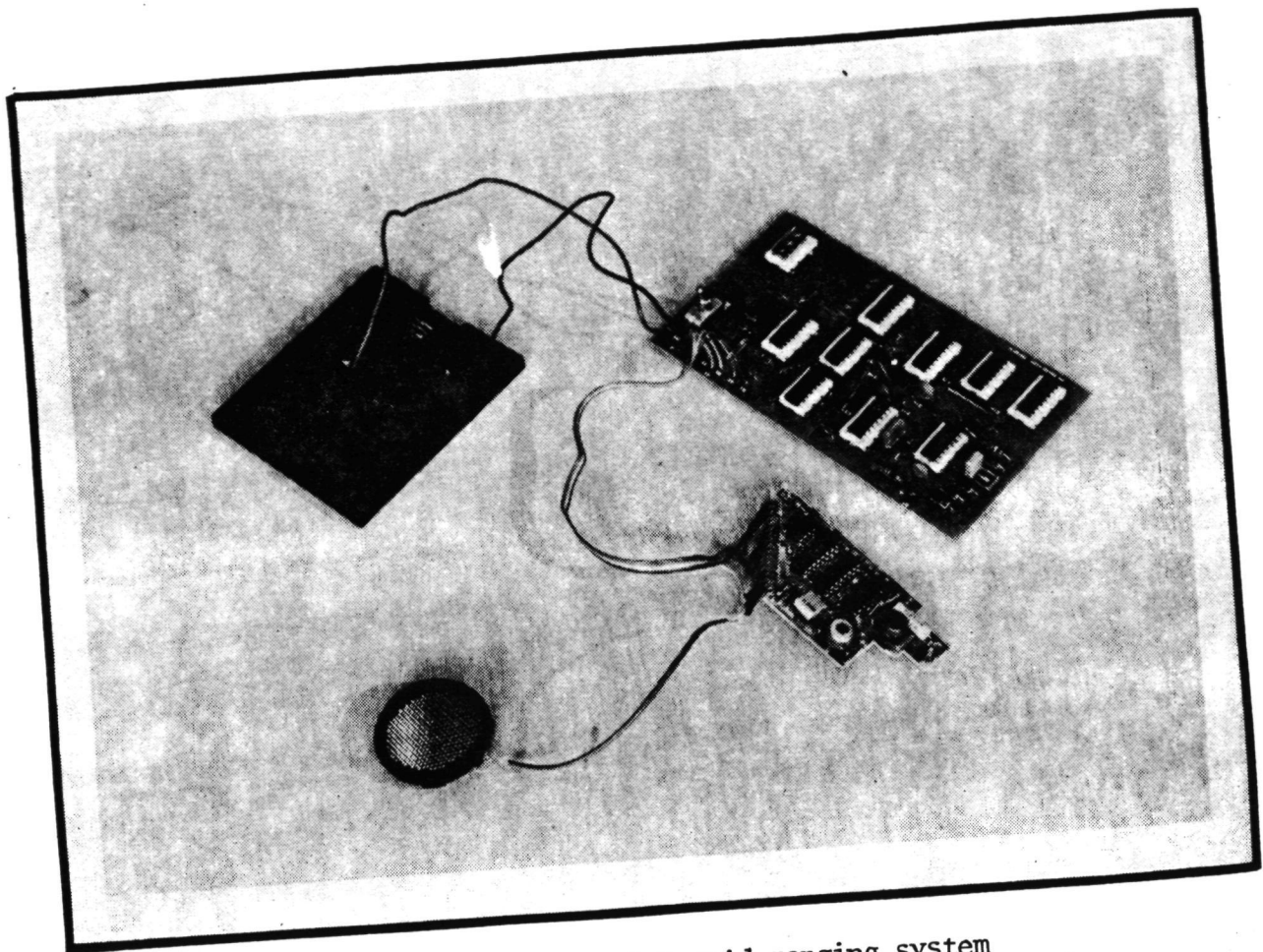


FIGURE 45 Polaroid ranging system
Main board is triangular
shaped. Large board con-
verts time to distance,
comparable to logic board.
Battery pack shown in up-
per left. Round object is
the capacitive ultrasonic
transducer.

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circuit of the echo-time system, interface circuits are suggested in Polaroid's manual for coupling the set and reset pulses needed. These are shown in figure 46 for completeness.

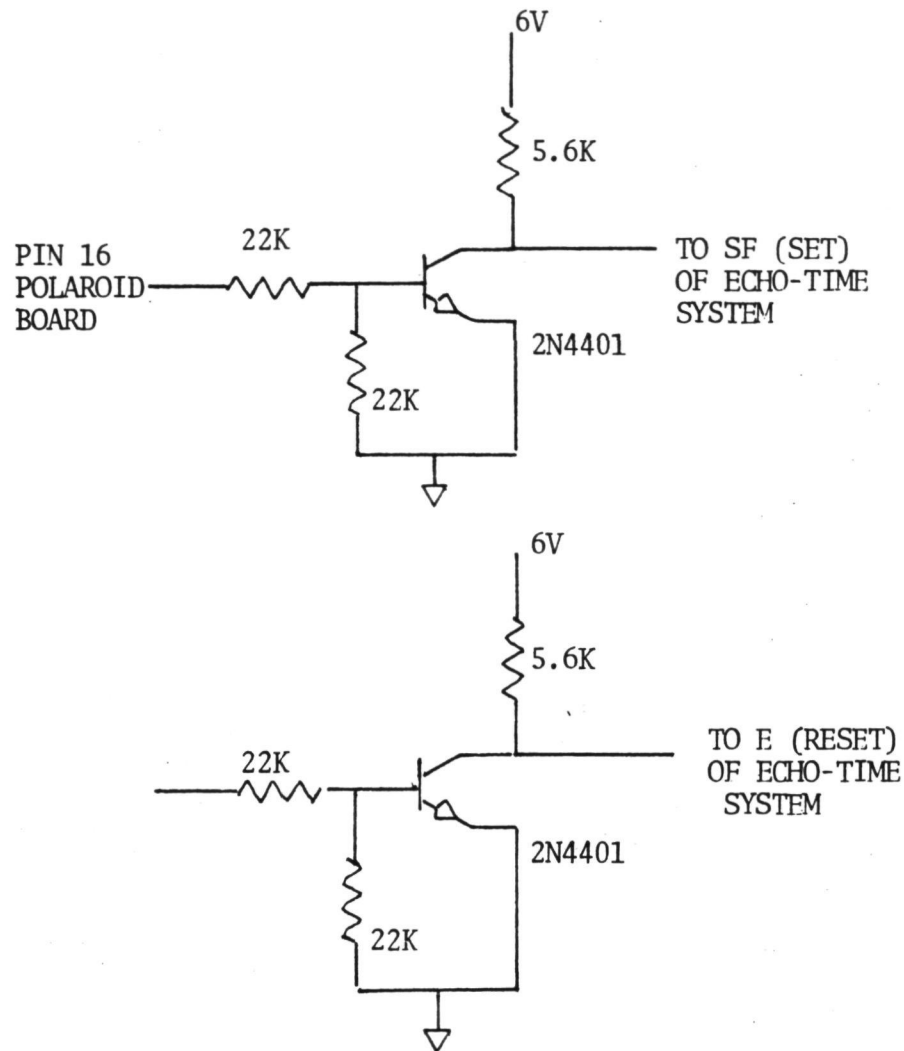


FIGURE 46. Polaroid system interface circuits. (From Polaroid manual)

VI. DOPPLER METHOD

Another cumulative technique, a doppler frequency method, was studied but not developed because of instability and the lack of sensitivity. Basically the system employed a phase-locked-loop (PLL) chip acting as an FM detector. The carrier frequency, set to the ultrasonic 40KHz, is the center frequency. Any variations around 40KHz, produced by the small frequency shift of the echo as the target moves, results in an analog output which can be accumulated in an integrator; since the integral of velocity is distance, the target range is obtained.

Unfortunately the frequency variations are small since the head moves at velocities very much less than that of sound. In fact, some slow movements were not even

detected by this system. For example, if the head moves 1 ft/sec, the theoretical difference between transmitted and echoed frequency is only about 34 Hz.

The final output was so erratic that it was not reliable. Techniques to heterodyne the 40KHz echo were tried, but the stability of the oscillator and slow head movement problems persisted. After a time this approach was abandoned for the echo-time and phase-shift methods which showed promise with the initial design. As time permits, this approach will be re-examined during the second year of this study.

VII. CONCLUSIONS

Each of the three systems discussed in this report have desirable characteristics, but each one also has some difficulties. The Polaroid system is accurate and almost has the sensitivity needed for the oculometer (1" desired, 1.2" for the Polaroid); but the beam width of the transducer does not cover a wide enough angular zone. The echo-time system is less consistent in its measurements, but has the beam width required. Finally, the phase-shift system has all the precision and beam width needed, but cumulative errors make it unreliable.

When all things are considered, the echo-time system appears to be the best system for oculometer application. The overriding criteria is the need for long experiments with the oculometer. The echo-time or Polaroid system

updates the range measurement many times a second so any errors will be short-lived. The combined echo-time and phase shift approach does not offer the best of both since any echo time error destroys the advantage of the precision of the phase shift method. In addition, it is possible for the phase shift system to lose count between echo-time updates which will compound errors. Simple RC filtering of the echo-time output is probably as good as the phase shift "add on" to give a smooth output.

One area of investigation that may yet prove advantageous is with the system transducer. Five different, inexpensive ultrasonic transducers have been used in the study, but models with greater sensitivity and radiation pattern may yield greatly improved operation without any major design changes. This subject will be considered in the future.

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